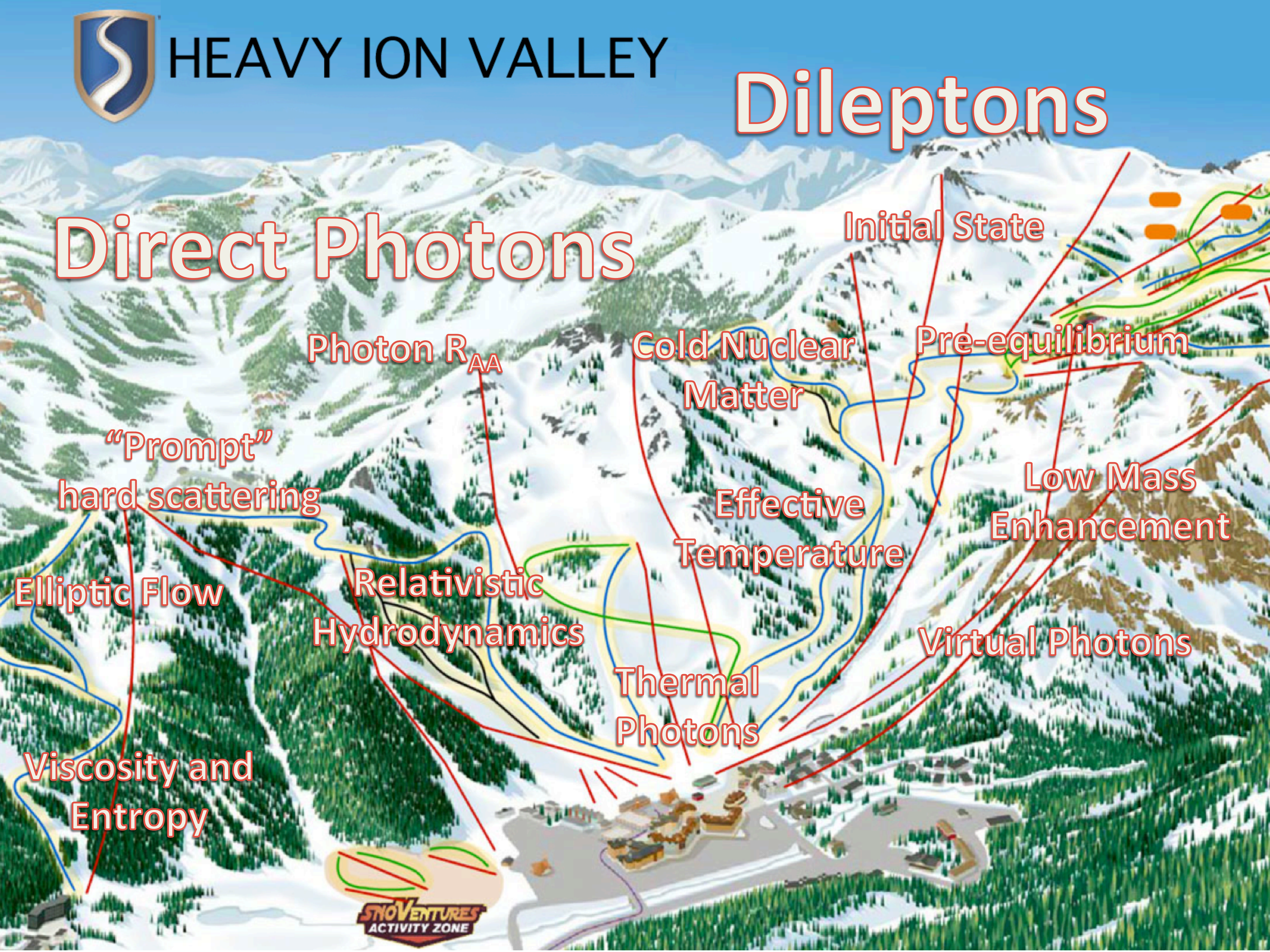
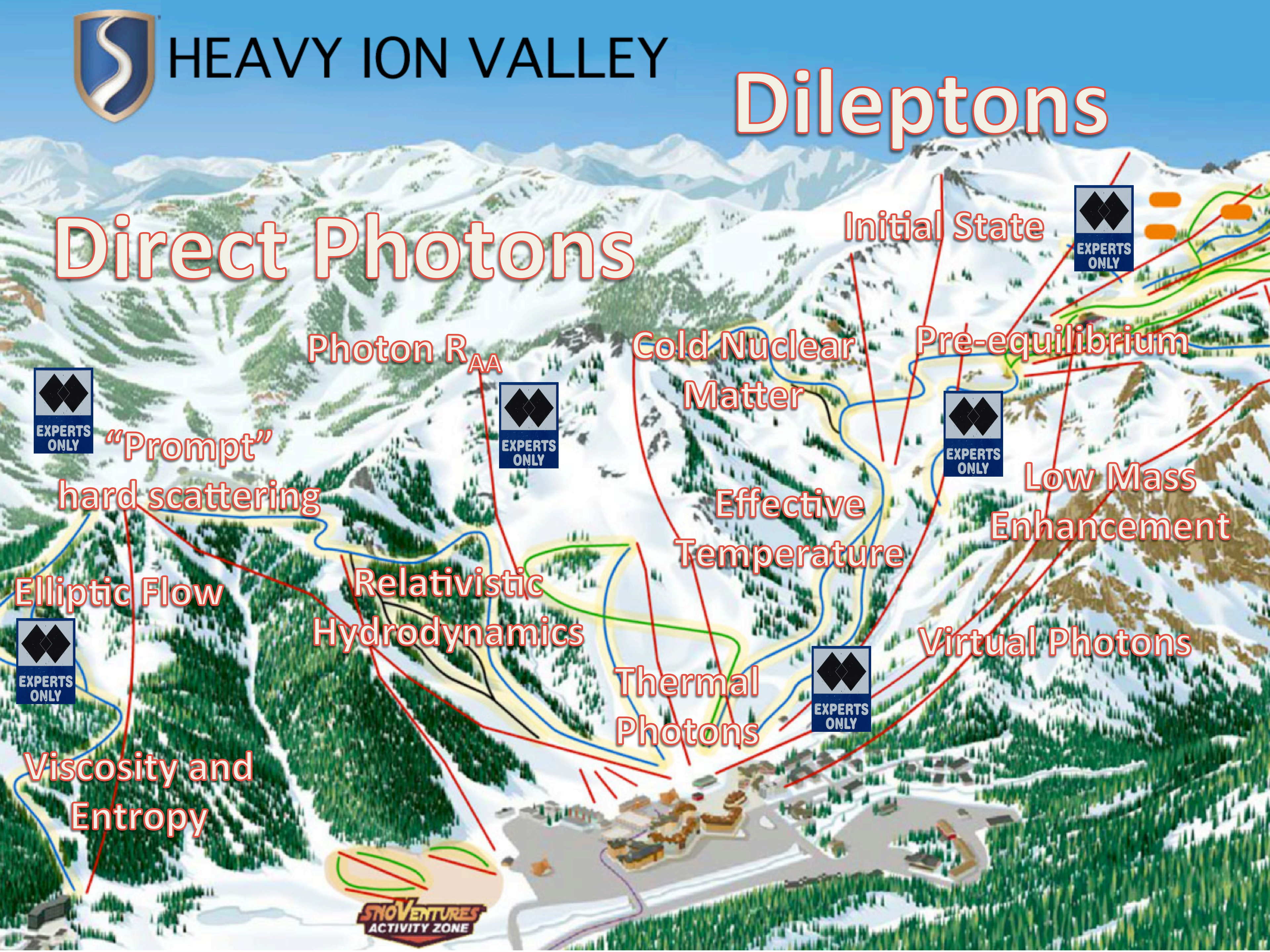
Winter Workshop Nuclear Dynamics 2013

Photons and Dilepton Measurements in PHENIX

Sky Rolnick
PHENIX Collaboration



HEAVY ION VALLEY
Dileptons
Direct Photons
Initial State
Photon R_{AA}
Cold Nuclear Matter
Pre-equilibrium
"Prompt" hard scattering
Effective Temperature
Low Mass Enhancement
Elliptic Flow
Relativistic Hydrodynamics
Virtual Photons
Thermal Photons
Viscosity and Entropy
SNOVENTURES ACTIVITY ZONE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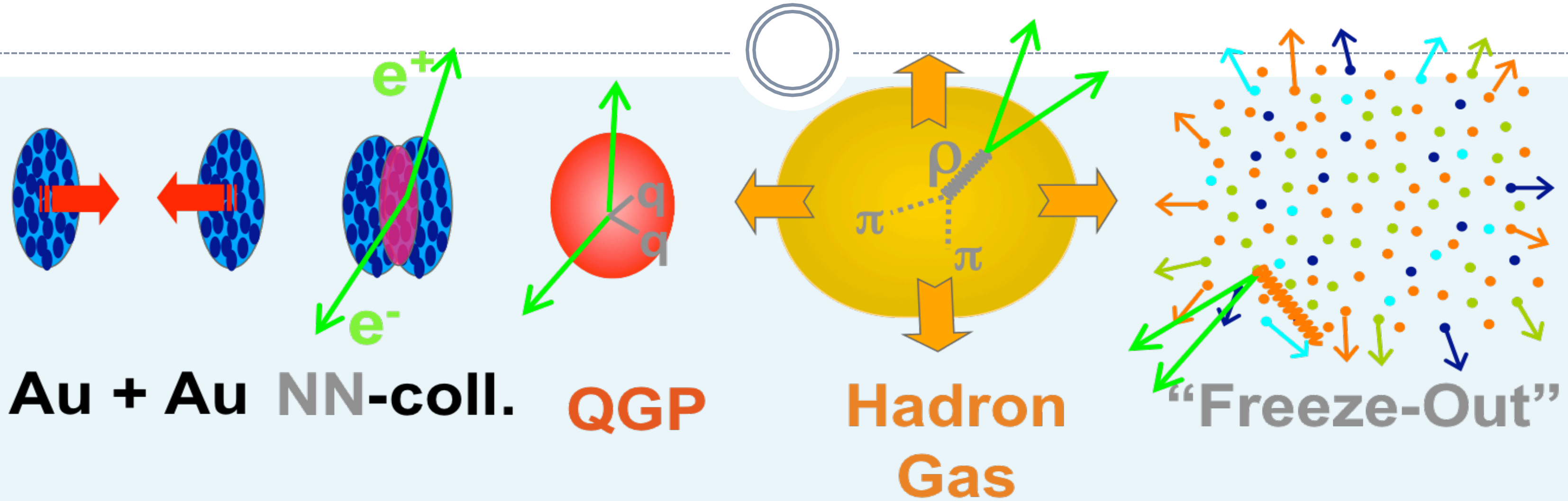
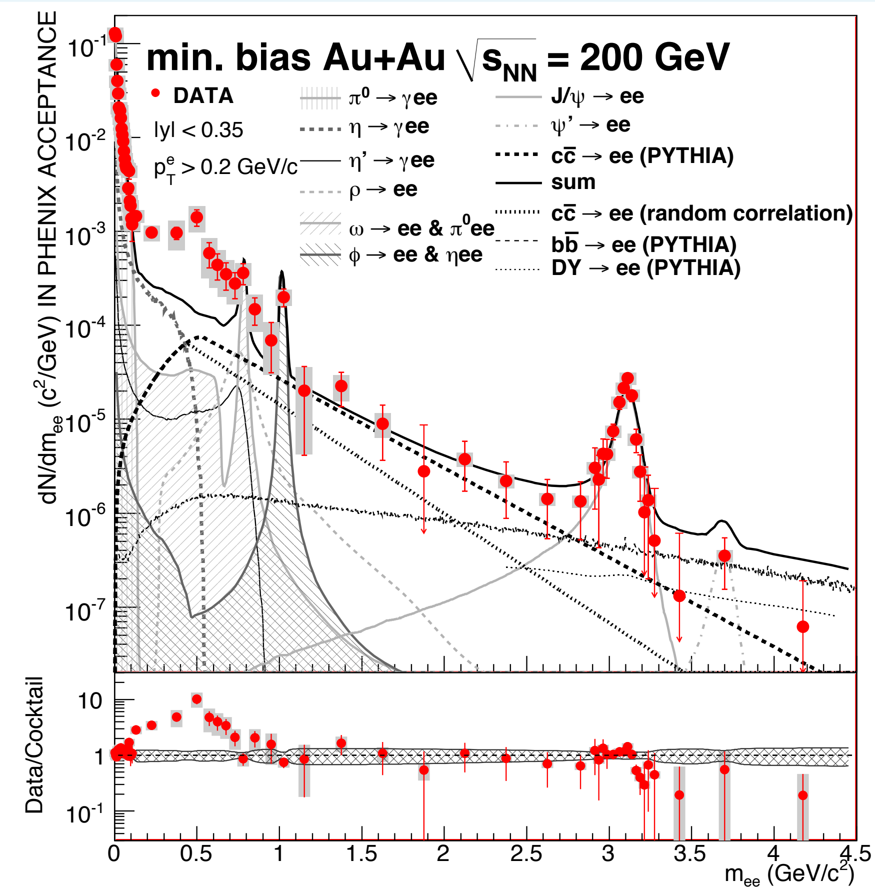
SNOVENTURES ACTIVITY ZONE

Heavy Ion Collisions



- Dileptons and photons are penetrating probes
- Produced during all stages of collision
- Very small interaction cross section with QGP
- Contributions from many production mechanisms
- Yields sensitive to temperature and collective motion of source

Dielectrons in PHENIX



PRC 81, 034911 (2010)

Low mass:
resonances/ Dalitz decays

Intermediate mass:
semi-leptonic heavy flavor

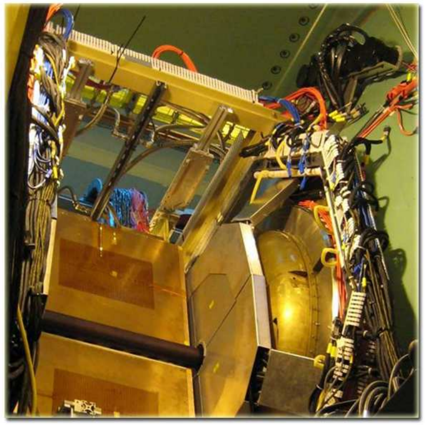
High mass:
resonances/hard processes

Strong enhancement of e+e- pairs at low masses, factor of $4.7 \pm 0.4^{stat} \pm 1.5^{syst} \pm 0.9^{model}$ (m=0.2-0.7 GeV/c²).

Currently no theory successfully explains this excess.

HBD Detector Concept

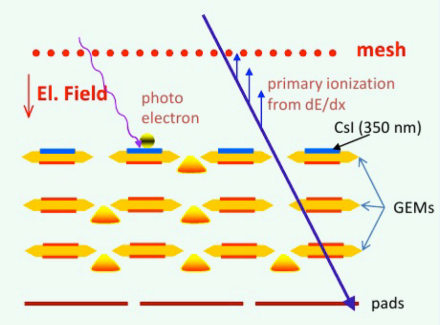
NIM A646, 35 (2011)



Successfully operated:

2009 p+p data

2010 Au+Au data



Windowless Cherenkov detector

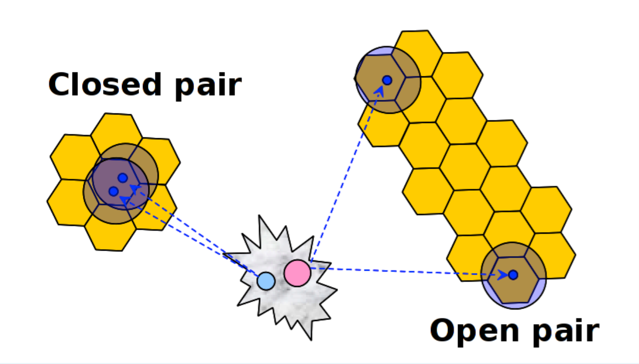
GEM, CSI photo-cathode

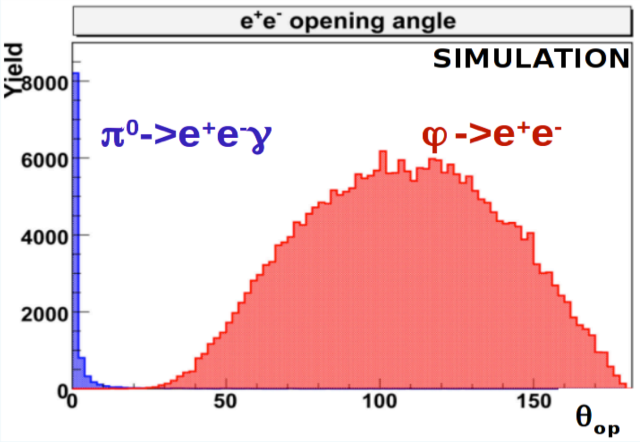
Pure CF4: $N_0 = 322\ cm^{-1}$

2.4% total radiation length.

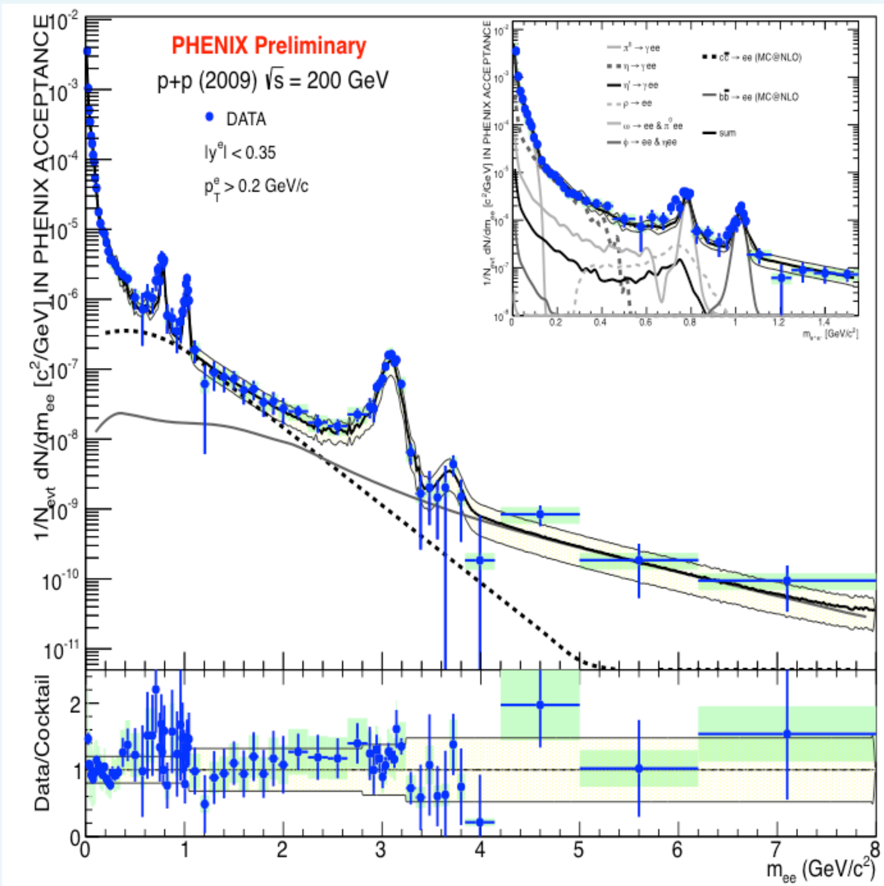
Heavier meson decays have large opening angles. Dalitz decays and conversions tightly peaked around $2m_e$.

Possible to identify e+e- from π^0 Dalitz decays and conversions by the opening angle.

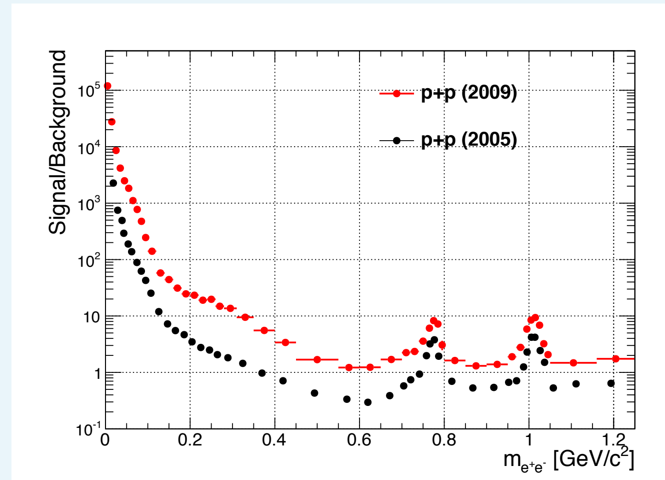




First Dilepton Results with HBD



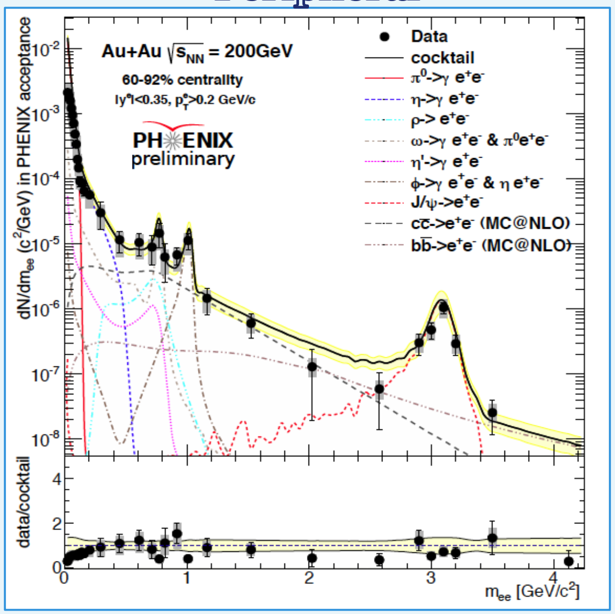
PHENIX 2009 data set



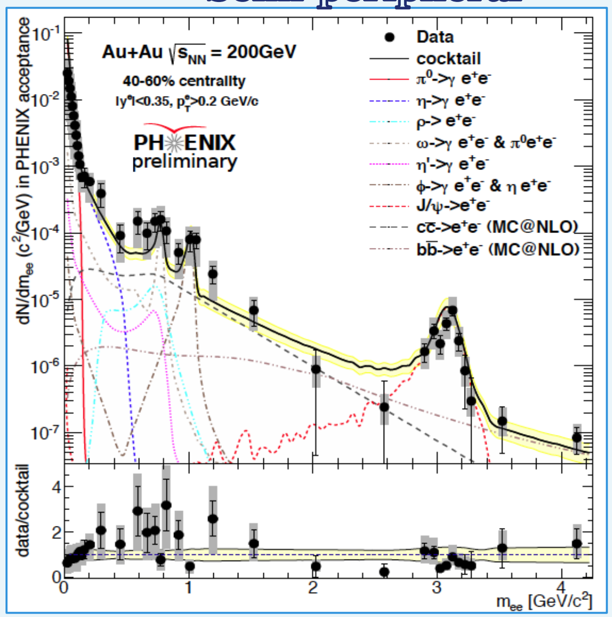
- Higher Statistics than 2005 data.
- Excellent agreement between data and cocktail.
- Baseline for Au+Au analysis, provides testing ground for understanding the HBD.
- Fully consistent with published result PR C81, 034911 (2010)

Dilepton Results in AuAu

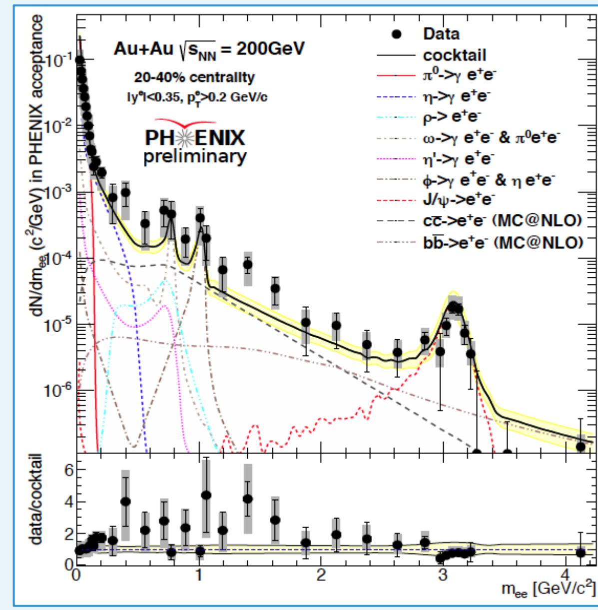
Peripheral



Semi-peripheral

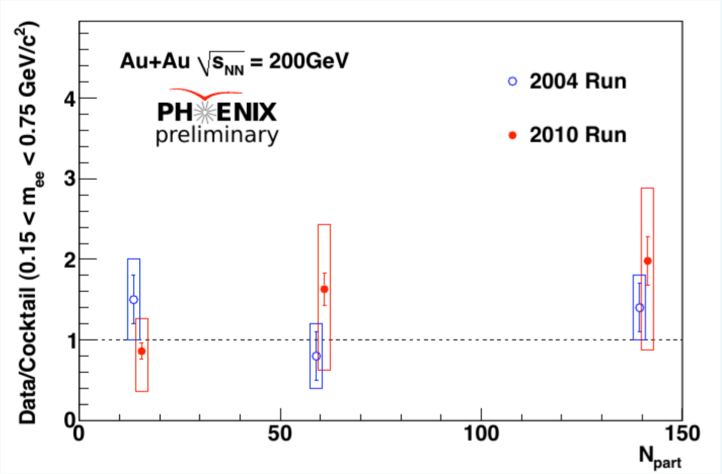


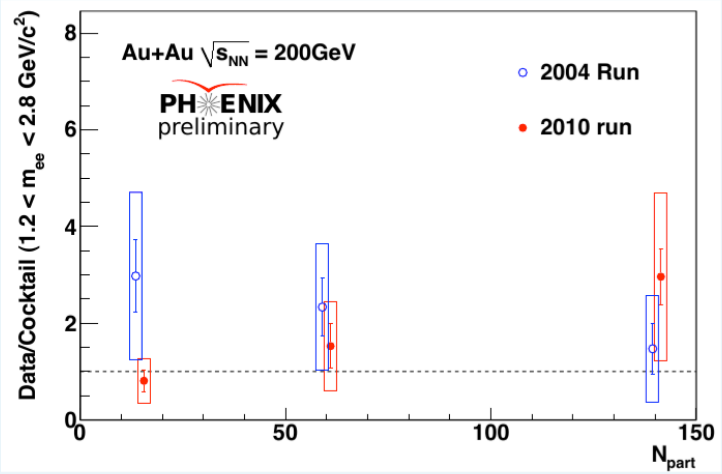
Semi-central



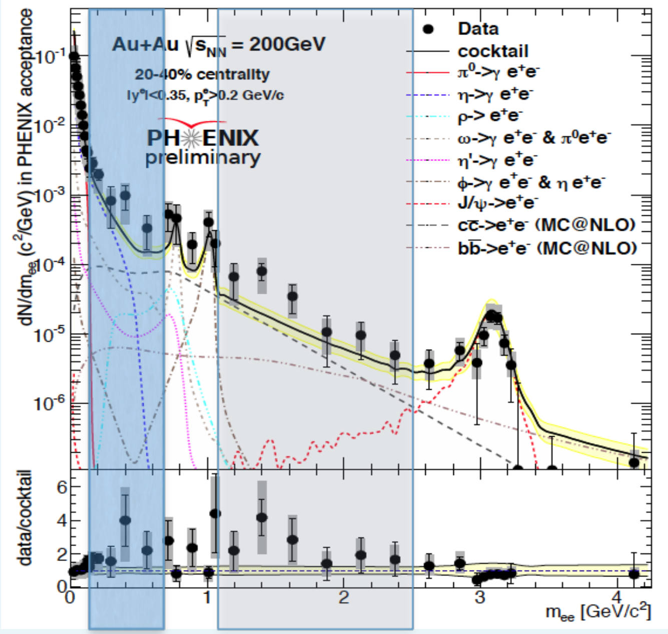
Dielectron Spectrum for 3 centrality classes: 60-92%, 40-60%, 20-40%

Au+Au Comparison





Semi-central



Data/Cocktail LMR (m=0.15-0.75 GeV/c²)	(value ± stat ± sys)
PHENIX Run 4 (20-40%)	1.4 ± 0.3 ± 0.4
PHENIX Run 10 (20-40%) (preliminary)	1.98 ± 0.3 ± 0.9

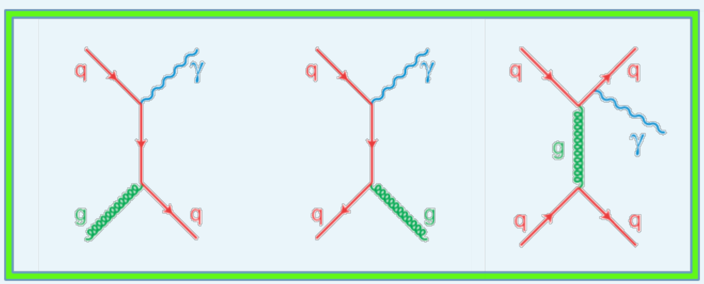
What are Direct Photons?

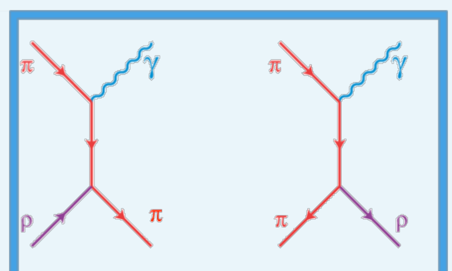
- Direct photons are anything not considered hadron decay photons.

$$\boxed{\gamma^{Direct} = \gamma^{All} - \gamma^{Decay}}$$

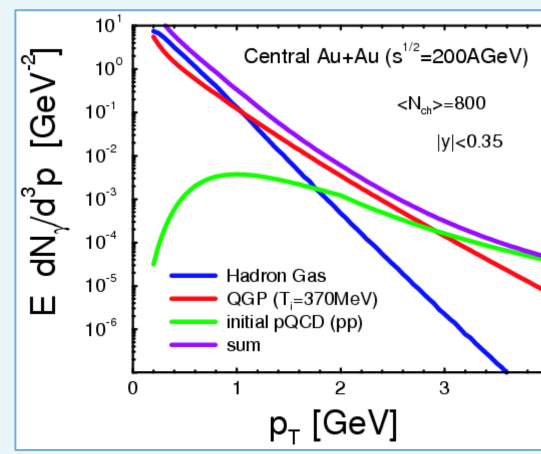
- There are several sources of direct photons. Each carrying specific information about the medium.

$$\boxed{\frac{dN_\gamma^{Direct}}{d^2 p_T dy}(M,b) = E\frac{dN_\gamma^{prompt}}{d^3 p} + E\frac{dN_\gamma^{QGP}}{d^3 p} + E\frac{dN_\gamma^{HG}}{d^3 p} + \ldots}$$





Turbide, Rapp, Gale,
Phys. Rev. C 69 (014903), 2004

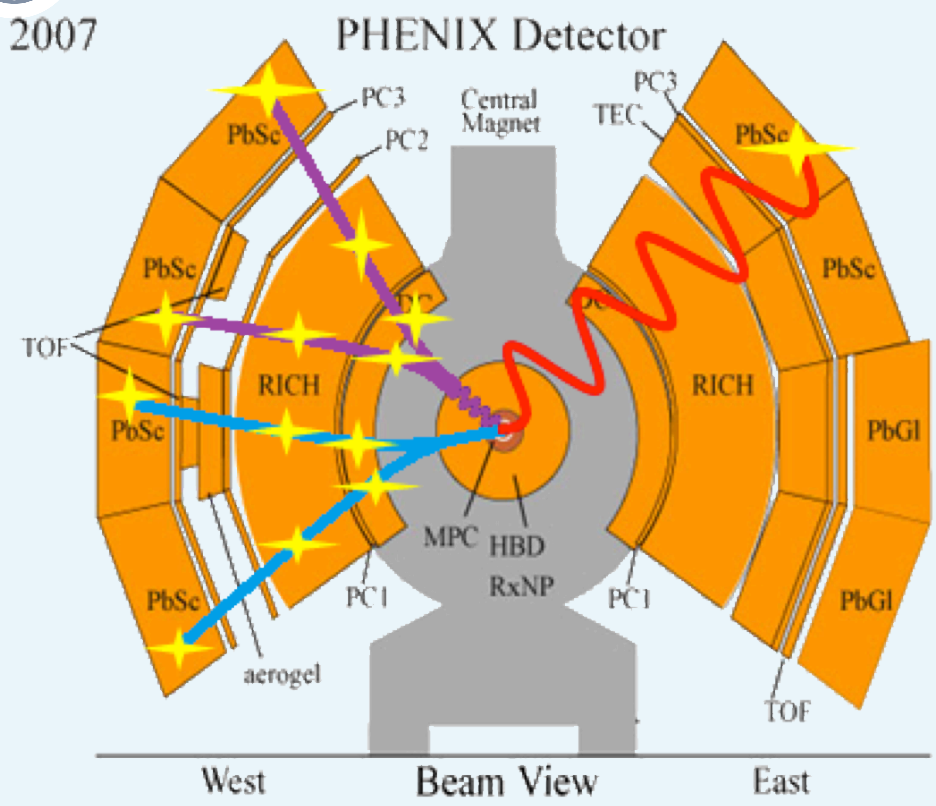


- Azimuthal anisotropy of direct photons should allow us to extract these different components.

Direct Photon Measurement methods

3 techniques at PHENIX

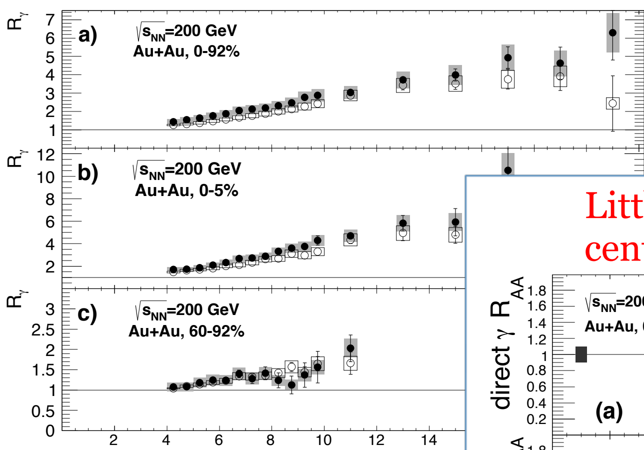
- Measure photons that directly deposit energy into the EMCal
  - Statistically subtract hadron decay γ from inclusive γ
  - Works best at higher momentum pT>5GeV/c
- Measure virtual photons that internally convert into e^+e^- pairs
  - Yield of virtual photons is related to real photon production
  - Allows a clean low p_T measurement pT<5GeV/c
- Measure real photons that externally convert in material into e^+e^- pairs
  - Complementary to virtual photon method



- Large background from hadron decays makes analysis difficult

Measuring Photons in Au+Au using EMCal

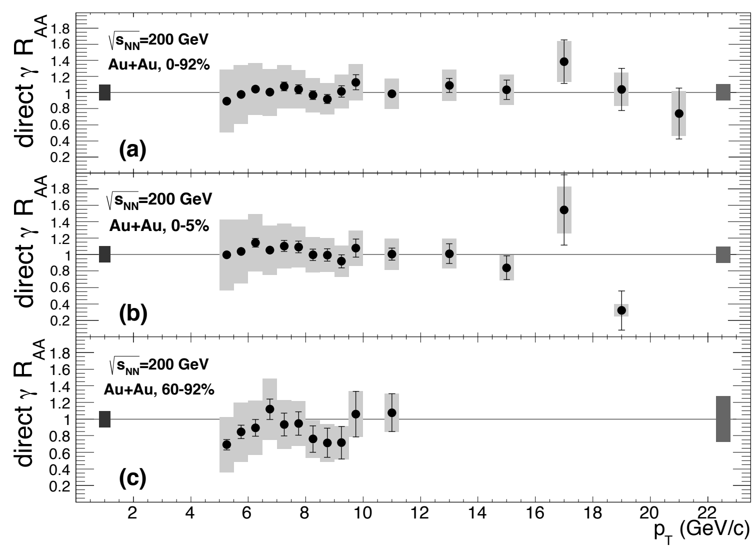
Excess above unity indicates signal



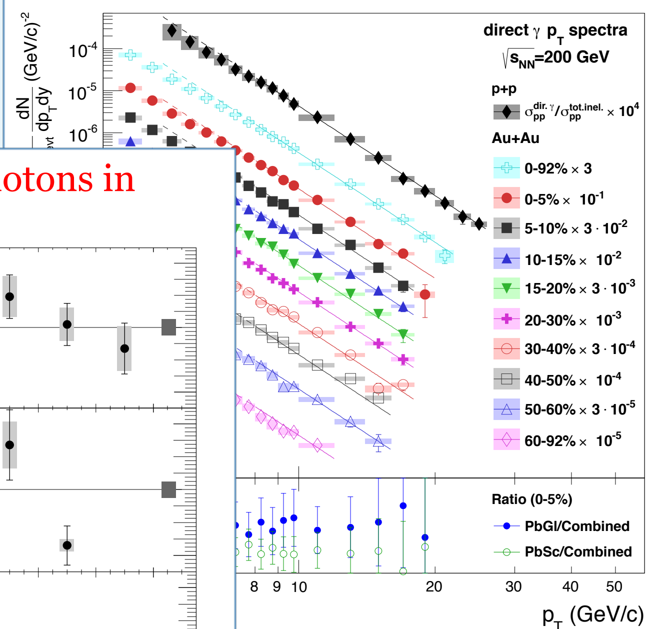
$$R_\gamma = \frac{\gamma_{data}^{inclusive} / \pi_{data}^0}{\gamma_{MC}^{decay} / \pi_{MC}^0}$$

PRL 109, 152302 (2012)

Little/no suppression of photons in central Au+Au



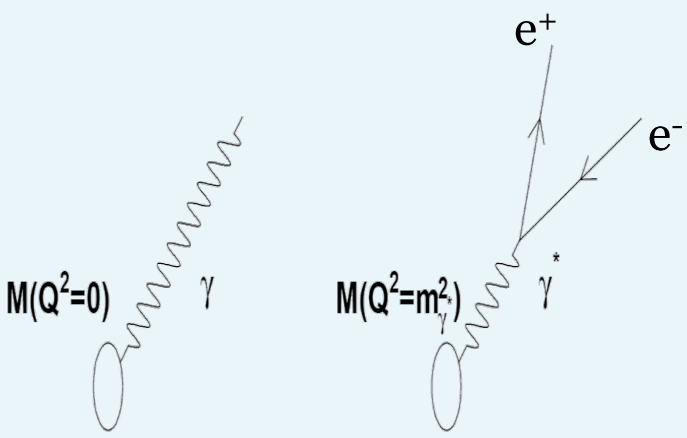
Direct photons by subtracting inclusive photons



$$(1 - 1/R_\gamma)\gamma^{inclusive}$$

More details in Sasha Bazilevsky talk

Relation between Real and Virtual Photons



Kroll-Wada Formula

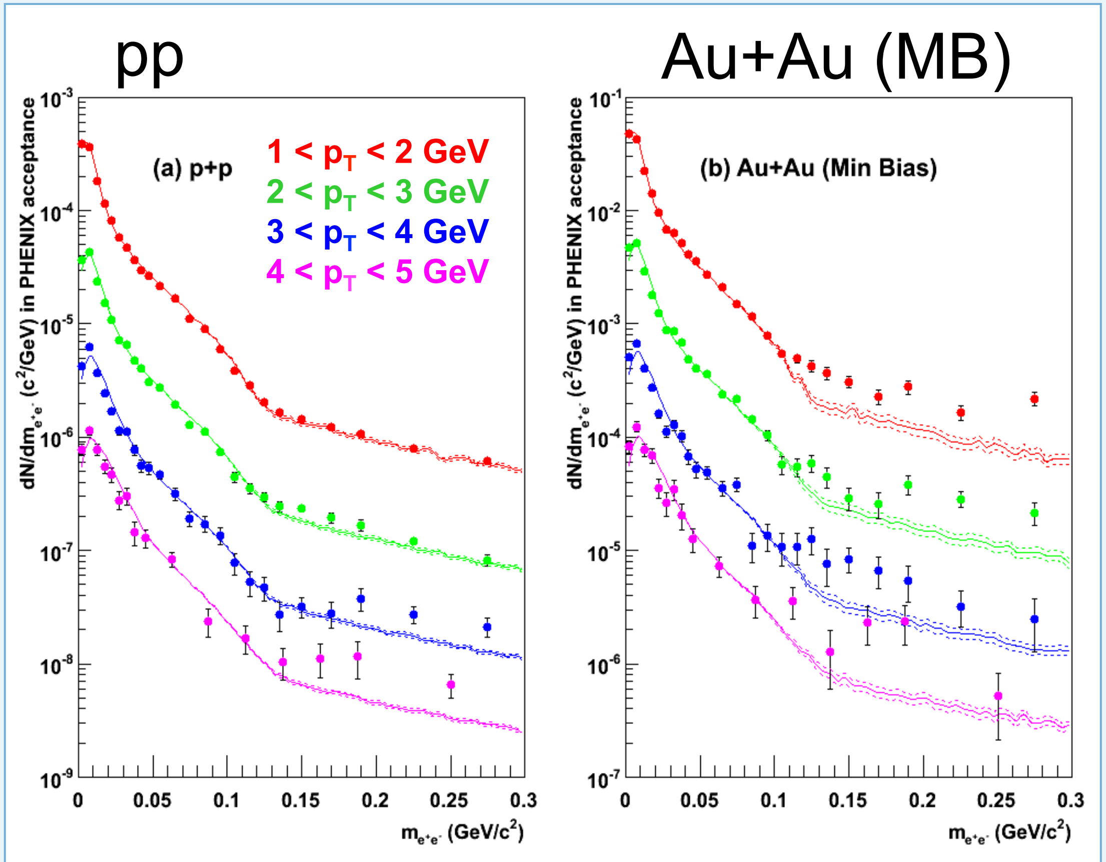
$$\frac{d^2N_{ee}}{dm_{ee}dp_T} \approx \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S(m,q)\frac{dN_\gamma}{dp_T}$$

As $m_{ee}/p_T \rightarrow 0$, then

$$\frac{d^2N_{ee}}{dm_{ee}dp_T} \approx \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\frac{dN_\gamma}{dp_T}$$

- Processes which produce real photons can also produce virtual photons which materialize as electron pairs.
- Real photon production can be determined from the excess electron pairs.

Enhancement of almost real photon



PRL 104, 132301 (2010)

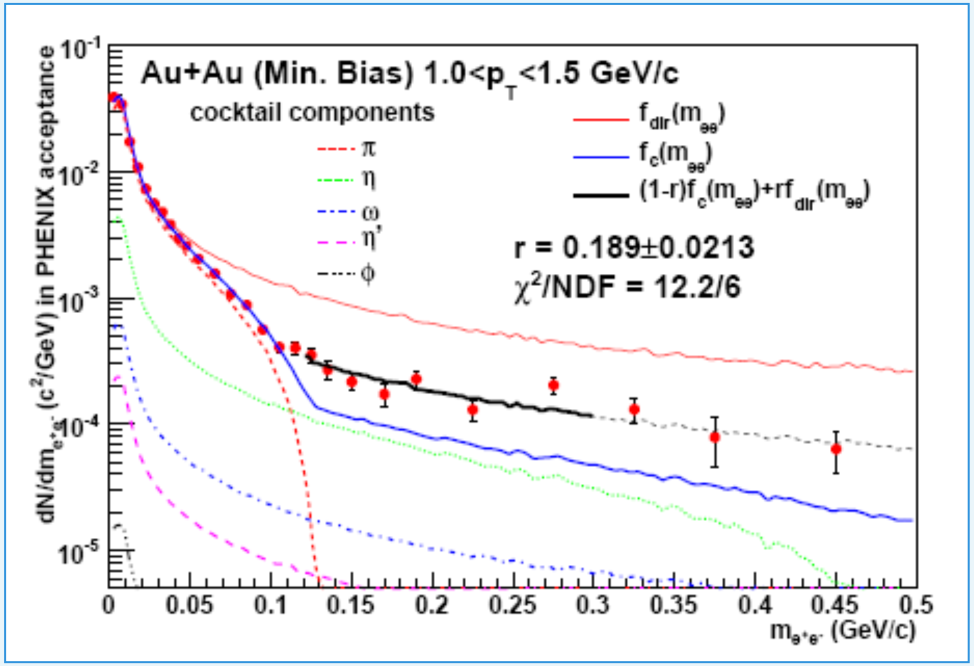
p+p

- Good agreement of p+p data and hadronic decay cocktail
- Small excess in p+p at large m_{ee} and high p_T

Au+Au

- Clear enhancement visible above π^0 mass for all p_T

Extracting the Fraction of Direct Photons

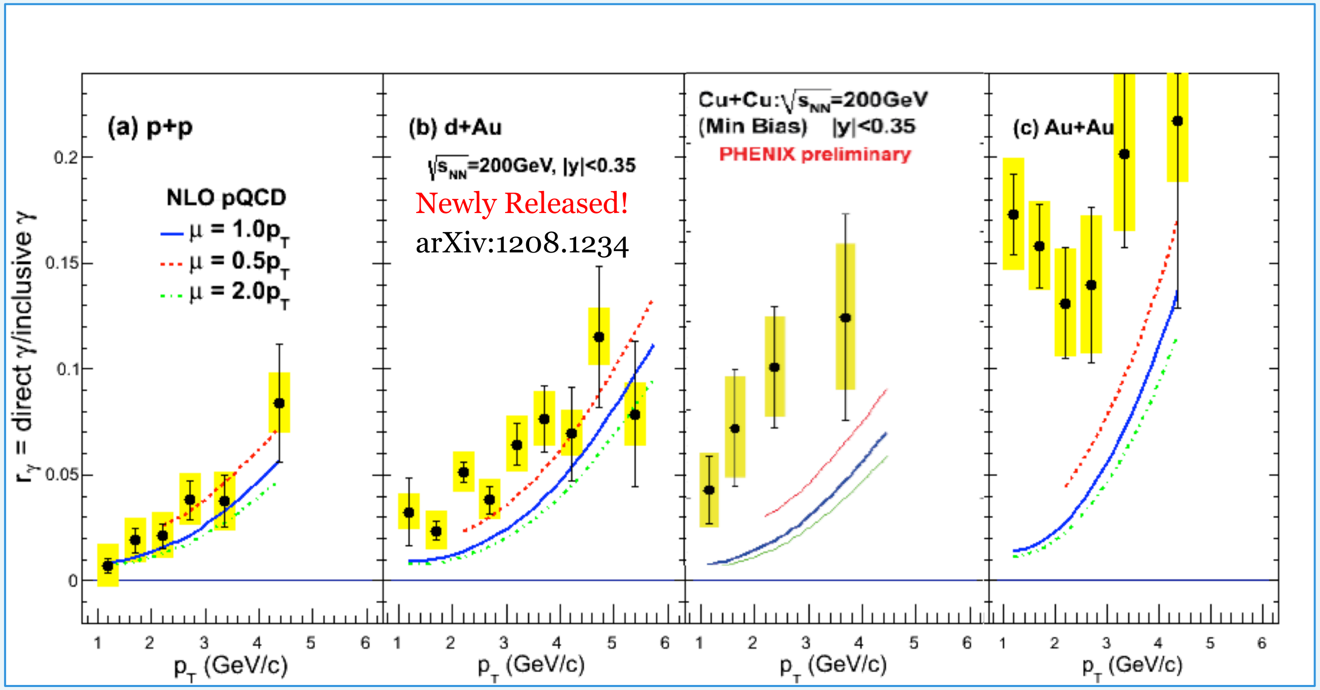


PRL 104, 132301 (2010)

- Measure low mass, high momentum dileptons
- Kinematic region of e^+e^- pairs $m<300$ MeV and $1<p_T<5$ GeV/c
- Analyze above π^0 mass to remove 90% of hadron background
- Fit mass distribution with a two-component function
- This excess is used to infer the yield of real direct photons by extrapolating to $m_{ee} = 0$.

$$f(m_{ee}) = (1-r)\cdot f_{cocktail}(m_{ee}) + r\cdot f_{direct}(m_{ee}) \quad \Rightarrow \quad r_\gamma = \frac{\gamma^*_{dir}(m>0.15)}{\gamma^*_{inc}(m>0.15)} \propto \frac{\gamma^*_{dir}(m\approx 0)}{\gamma^*_{inc}(m\approx 0)} = \frac{\gamma_{dir}}{\gamma_{inc}}$$

Direct Photons In Different Systems



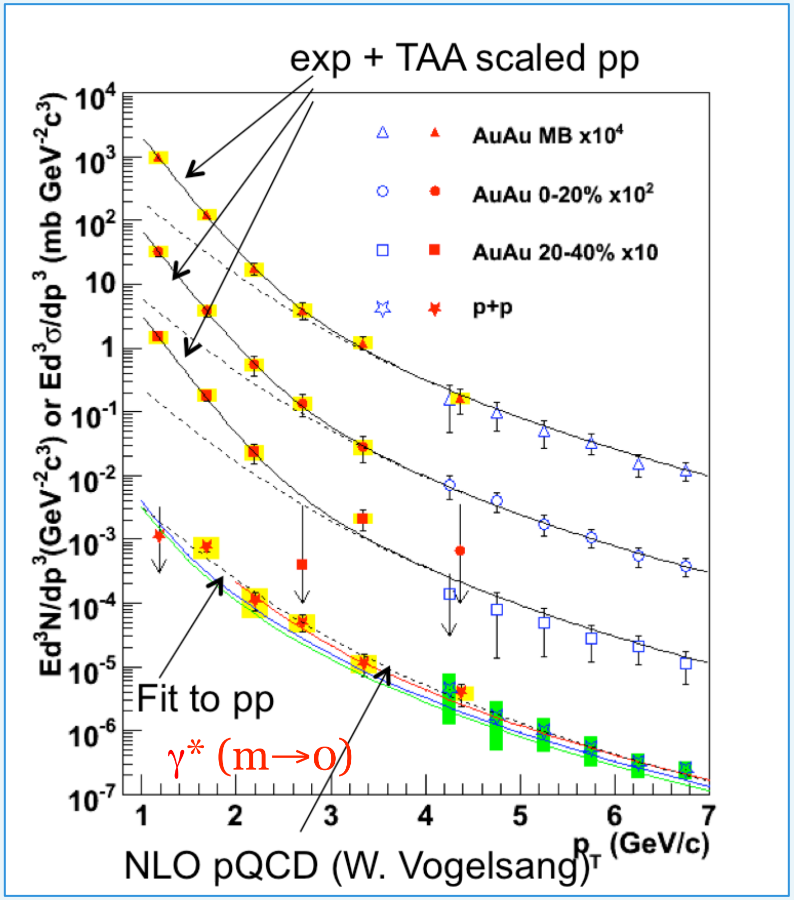
- PHENIX has measured low p_T direct photon ratio in various collision systems, showing clear enhancement in Au+Au and Cu+Cu.
- Essentially no enhancement is observed for p+p and d+Au.
- CNM effect measured in d+Au does not explain the excess in Cu+Cu Au+Au

Direct Photon Production in PHENIX

$$\gamma_{direct} = \gamma_{incl.} \cdot \frac{\gamma^*{}_{direct}}{\gamma^*{}_{incl.}}$$

- For p+p consistent with pQCD down to p_T=1 GeV/c
- For Au+Au there is a significant low p_T excess above p+p expectations.
- Exponential consistent with thermal

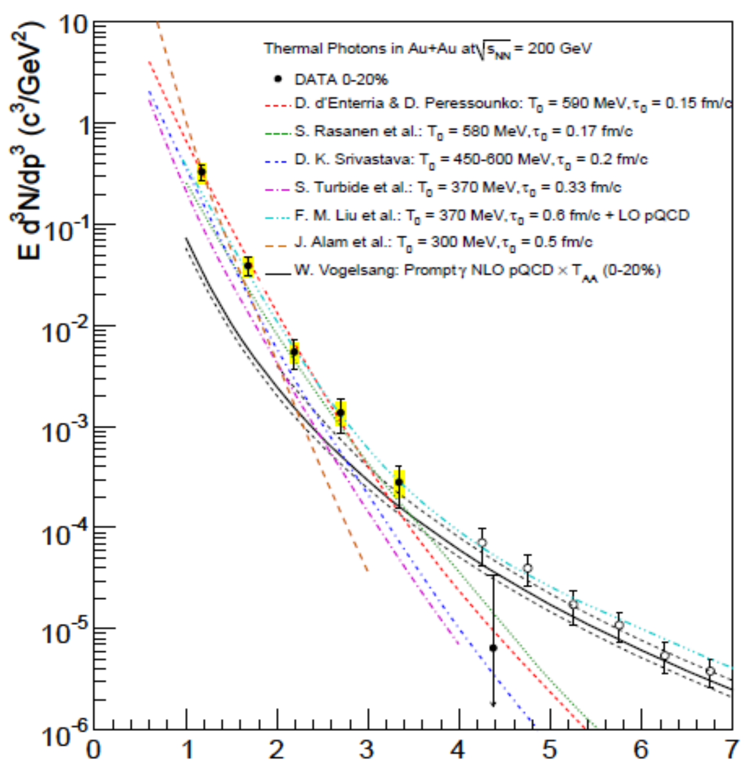
$T_{ave} = 221 \pm 19^{stat} \pm 19^{sys}$ MeV



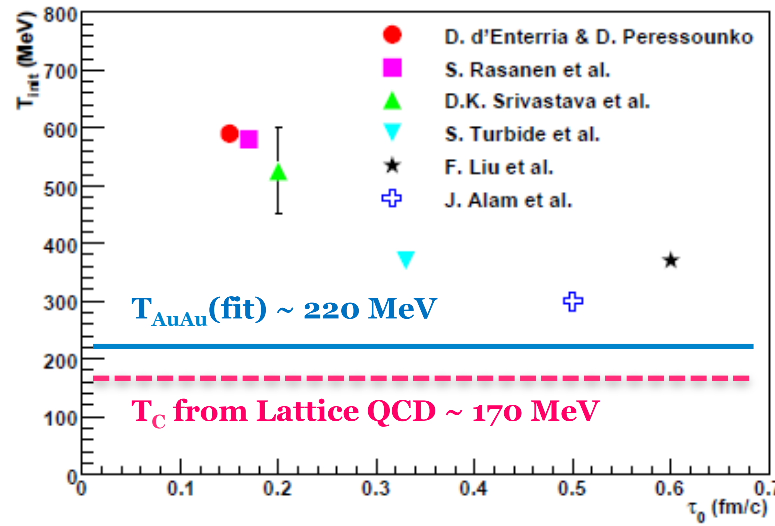
A. Adare et al., PRL104,132301(2010)

Comparing the Yield to Theory

Derive limits on temperature by interpreting excess as Thermal Radiation

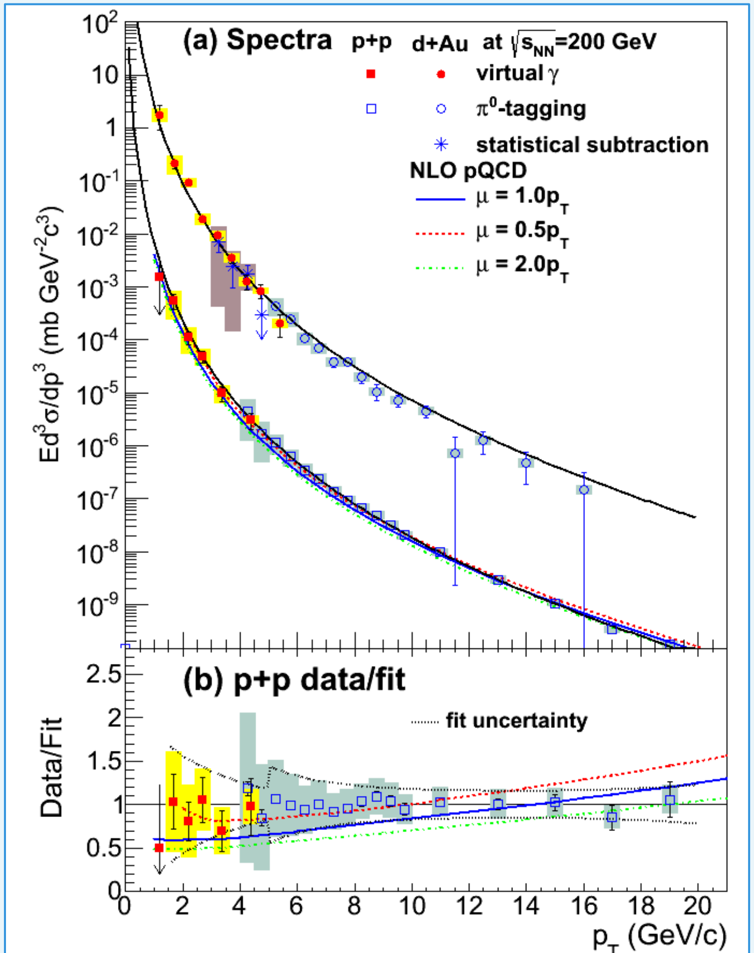


Phys. Rev. C 81, 034911 (2010)



- Fitting excess has slope of T~220MeV implies initial temperature of 300-600 MeV depending on model.
- Thermalization time range from about 0.6 to 0.15 fm/c

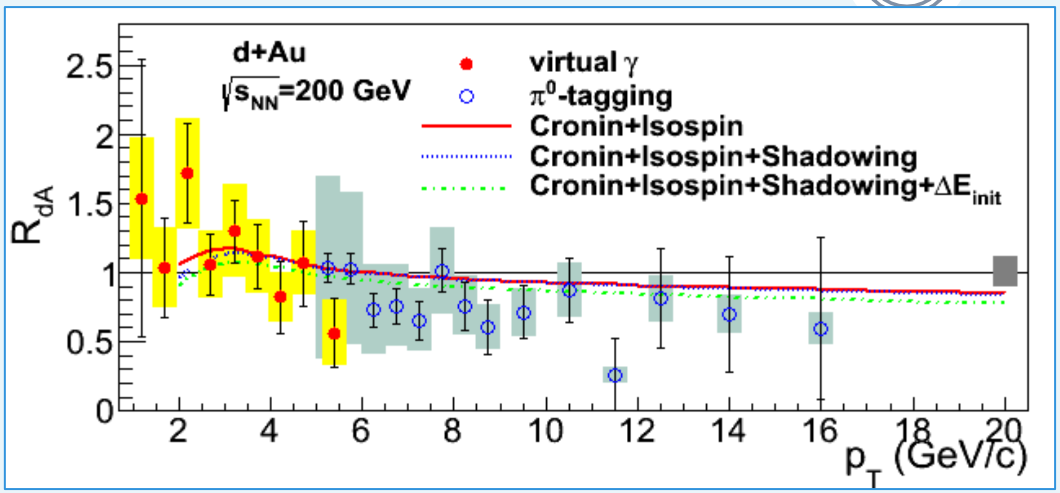
Direct photons in d+Au

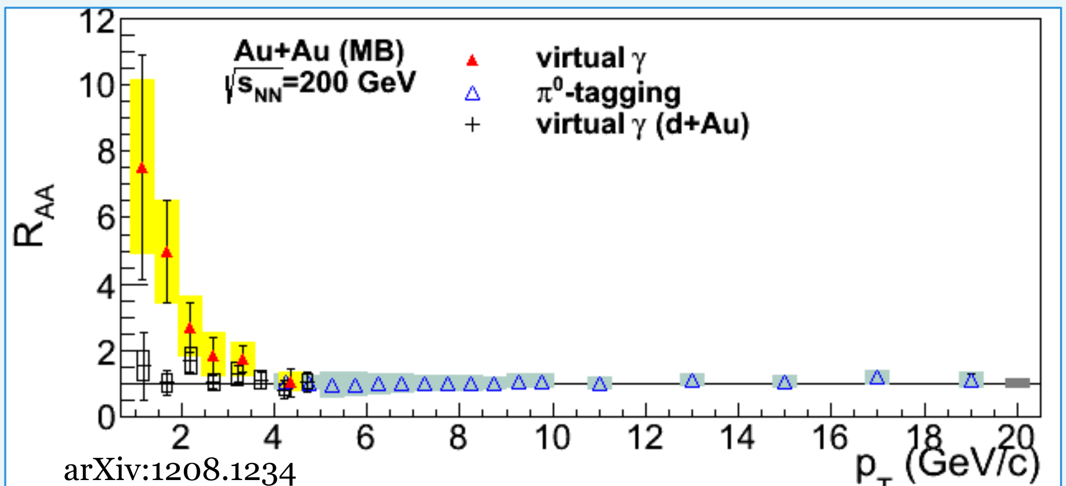


arXiv:1208.1234

- Direct photons in d+Au measured via 3 independent methods:
  - virtual photons
  - πo tagging
  - statistical subtraction
- The NLO pQCD fit to the p+p data, scaled by Ncoll, reproduces well the d+Au data
- No excess of photons.

Direct photons in d+Au and Au+Au



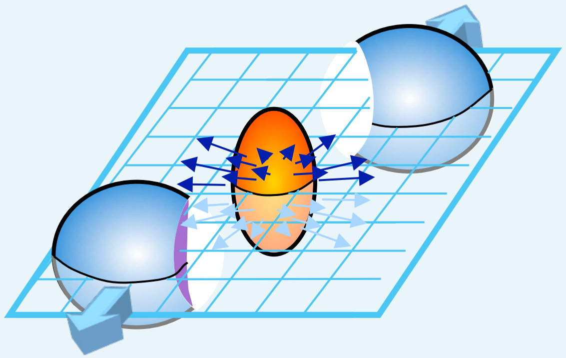


- R_{dA} is consistent with unity
- No excess in d-Au collisions

- Large excess of γ observed in Au+Au is not due to initial state effects
- Reinforce interpretation of the Au+Au excess as thermal radiation.

Direct Photons & Collective Flow

- Elliptic Flow



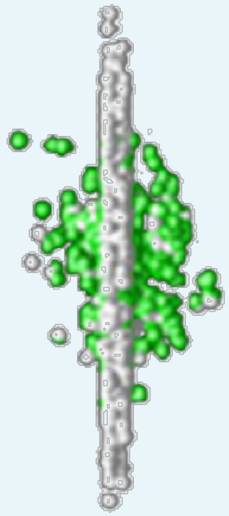
- A nucleus-nucleus collision is typically not head on.
- Overlapping region forms initial almond-shape anisotropy.
- Spatial anisotropy → p_T anisotropy

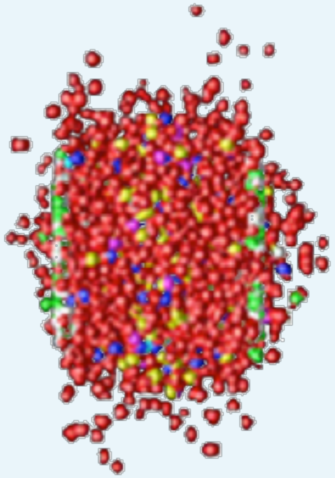
- To describe the evolution of the shape use a Fourier decomposition, i.e. flow coefficients v_n

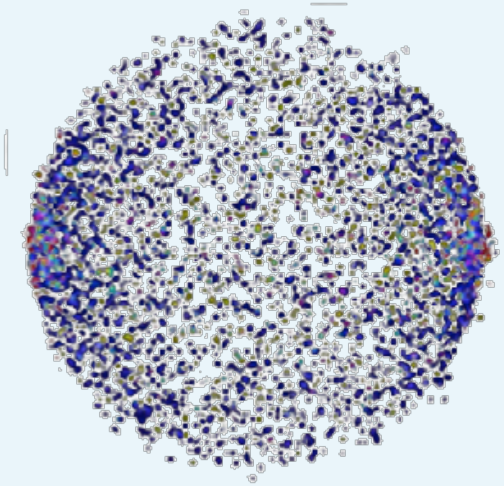
- Large azimuthal anisotropies in the particle emission are collective phenomena.

Disentangling the sources

- Measurements of v2 could give information on specific stages of the fireball expansion.







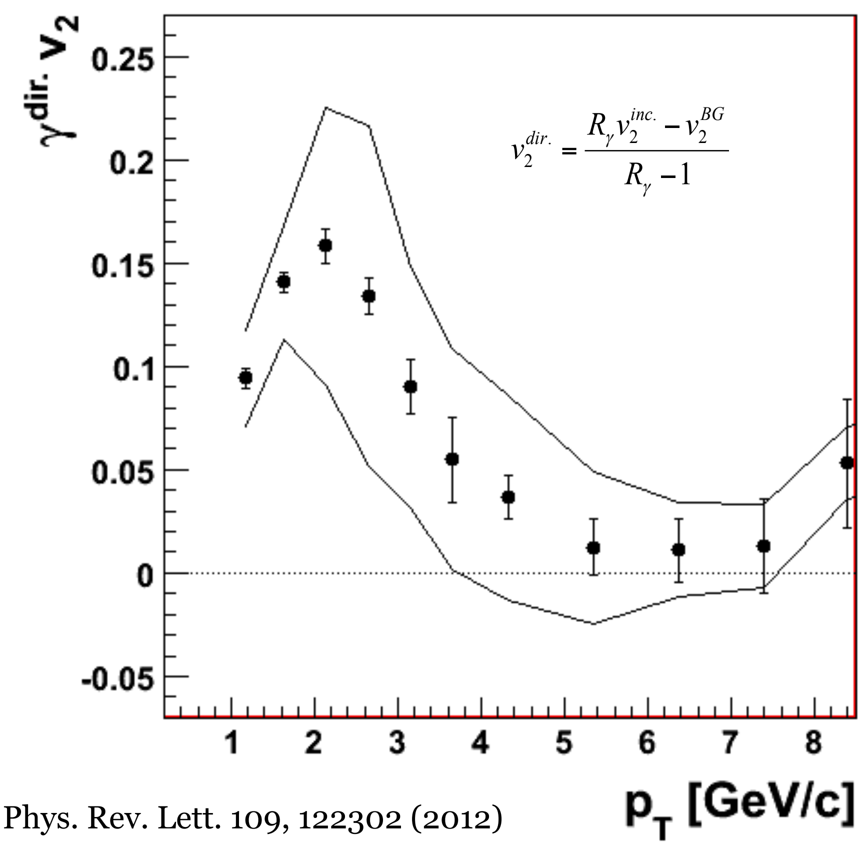
Initial collision
Hard scattering of partons v2=0
Pre-thermalized radiation v2=?

QGP
Thermal radiation v2>0
Jet Fragmentation v2>0
Bremsstrahlung v2<0
Jet conversions v2<0

High p_T phenomenon.
Reflective of geometry not dynamics.

Hadron Gas
Thermal radiation v2>0

Direct photon Elliptic Flow



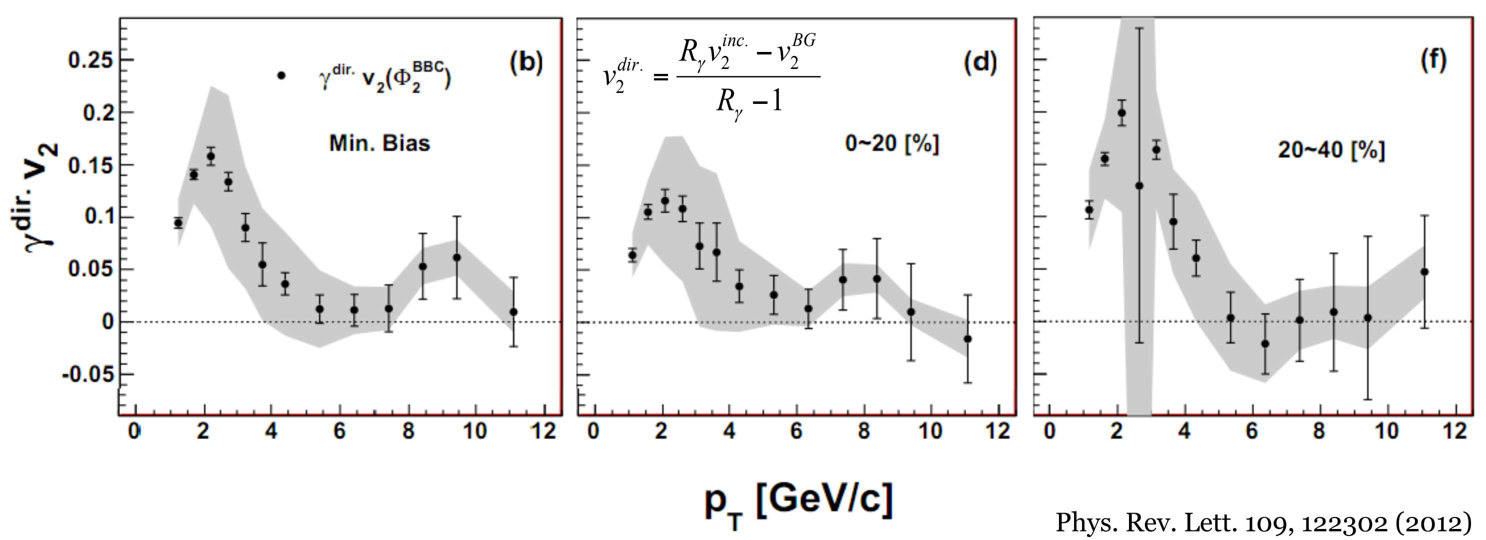
Phys. Rev. Lett. 109, 122302 (2012)

How to determine elliptic flow of direct photons?

- Establish R_γ as fraction of inclusive photons over decay photons.
- Measure v_2 for inclusive photon yield correcting for hadron contamination.
- Predict hadron decay photon v_2 from measured pion v_2 and ncq scaling of other hadrons.
- Subtract hadron decay contribution from inclusive photon v_2 to arrive at direct photon v_2.

$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

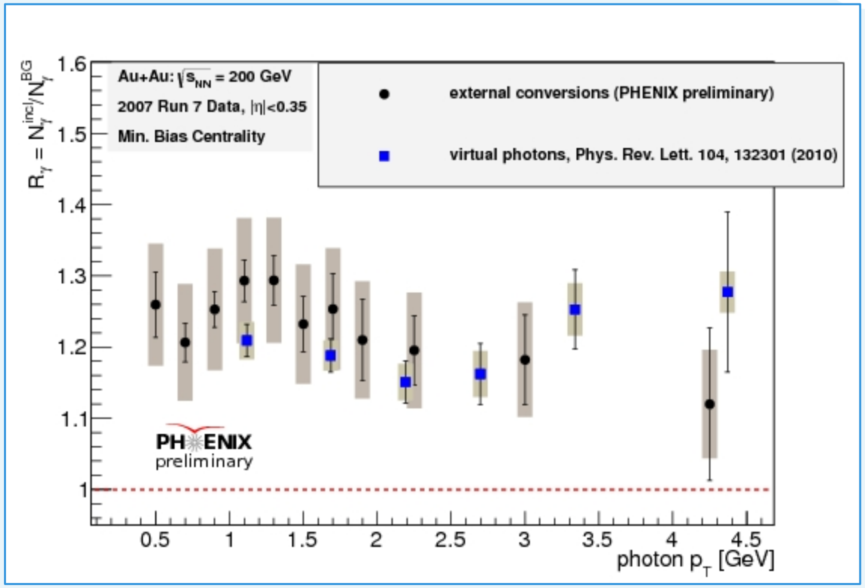
Direct photon v_2



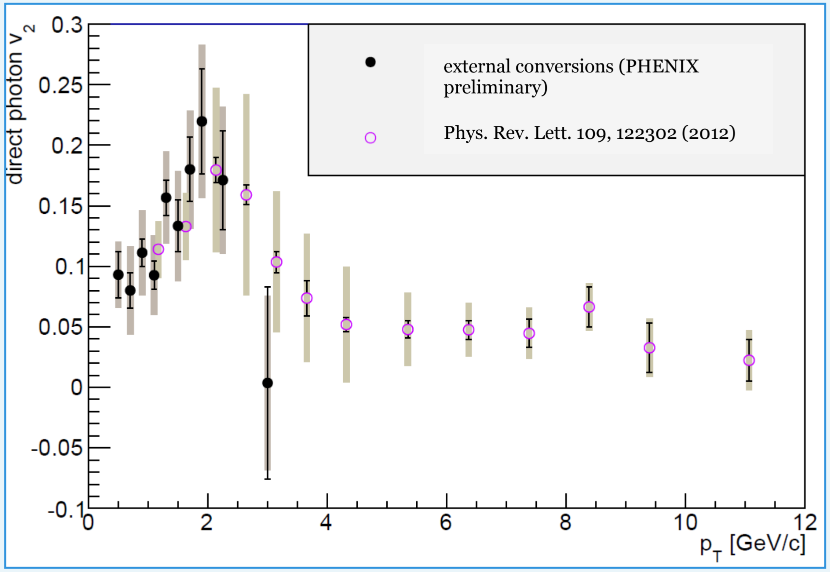
Phys. Rev. Lett. 109, 122302 (2012)

- We observe a significant direct photon signal with significant v_2
- Similar to inclusive photon and π^0 v_2 at low momentum
- v_2 drops to zero for $p_T > 5$ GeV, where hard processes dominate

Nice Crosscheck: External Conversions!

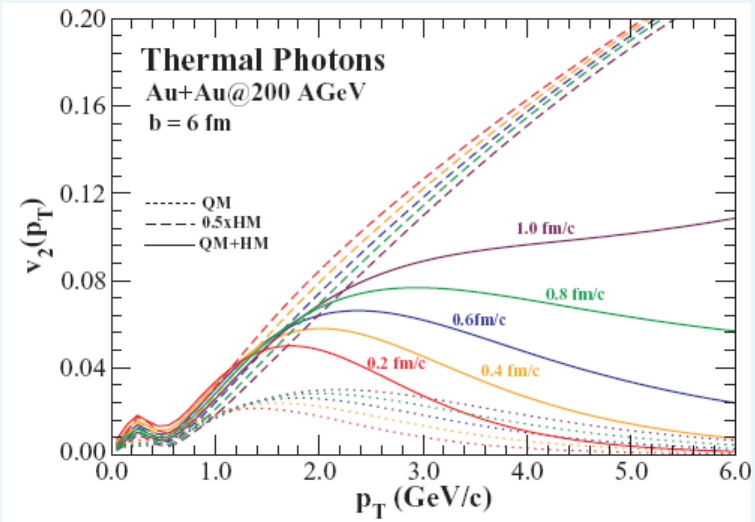


- Independent analysis
- Different systematics
- pT range extended down to 0.5 GeV/c

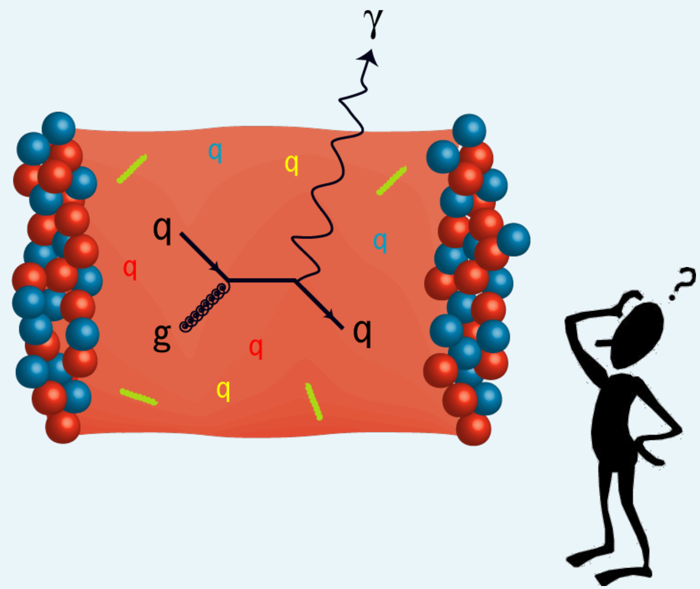


$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

Thermal Photon Puzzle



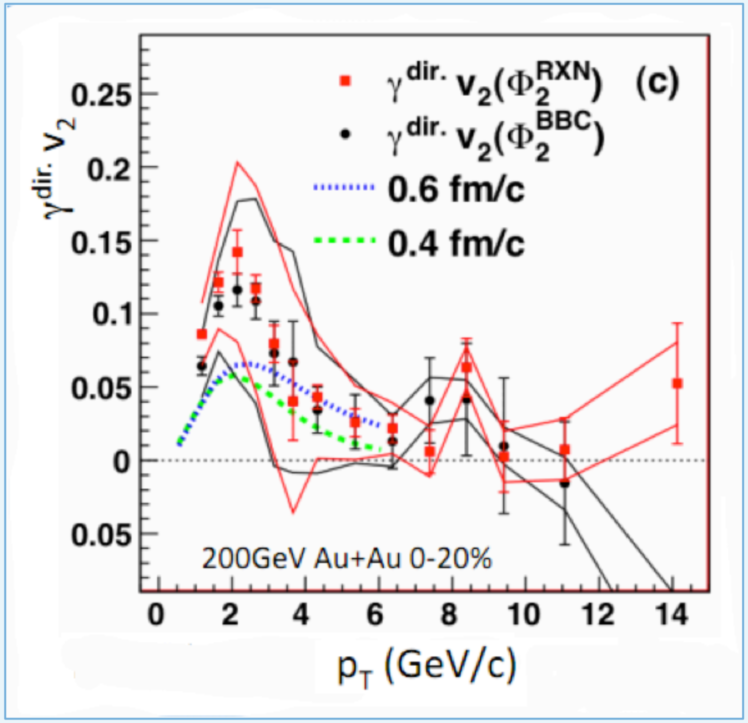
R. Chatterjee & D. K. Srivastava, **PRC 79, 021901 (2009)**



- Very surprising result: large v2 implies late emission whereas high temperature implies early emission.
- Difficult to reconcile with the current understanding of the evolution. Theory mostly underpredicts.
- Possibly other sources of low p_T photons other than thermal radiation?

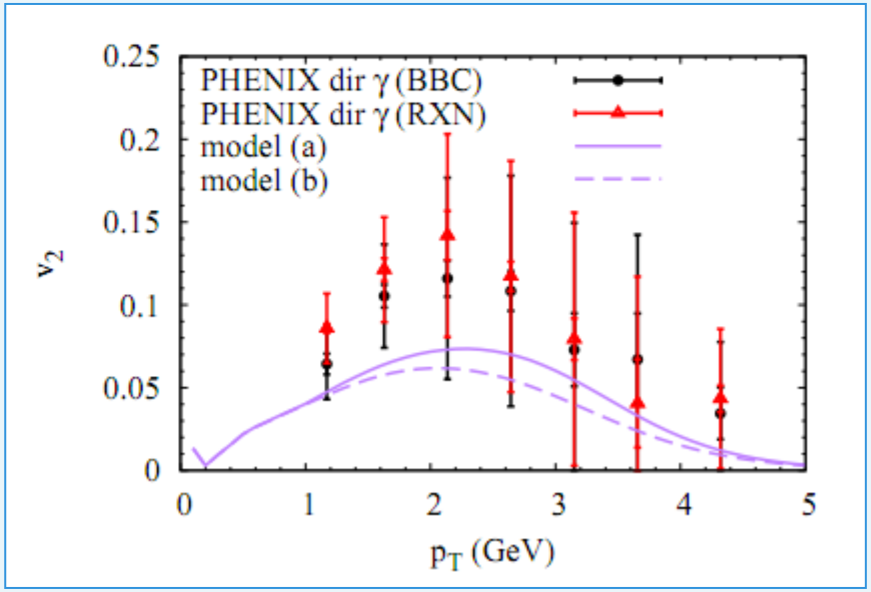
What does it mean? Compare to theory

Chatterjee, Srivastava PRC79, 021901 (2009)
PHENIX, arXiv:1105.4126



Hydrodynamics with a thermalization at early times followed by hadronization and decoupling.

H. van Hees, C. Gale, R. Rapp
Phys. Rev. C 84, 054906 (2011)



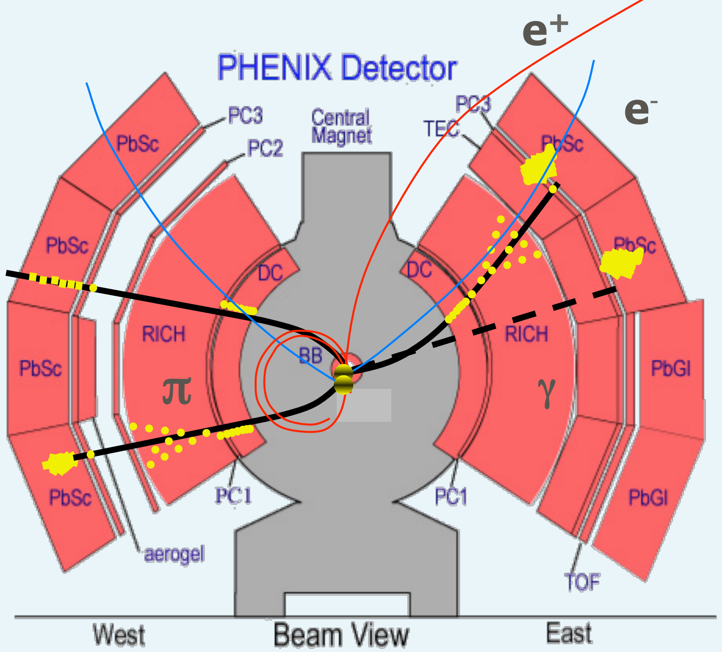
Thermal radiation dominated by hadronic phase. Hadronic phase lasts longer and elliptic flow builds up faster.

Summary & Conclusions

- Electromagnetic radiation has great potential to explore general properties and early time dynamics of Quark Gluon Plasma.
- Looking at dielectron pairs is a nice tool to get a clean direct photon signal at low p_T
- PHENIX has measured direct photons in various collisional systems (including baseline p+p, d+Au, Cu+Cu, and Au+Au)
- No significant enhancement in the baseline systems p+p and d+Au, but significant enhancement in A+A
- Large elliptic flow observed for direct photons which remains a bit of a mystery.
- Theorist are working on reconciling these measurements.

BACKUP SLIDES

Dielectrons in PHENIX



Detector	Δη	Δϕ	Field
PHENIX Central Arms	+/- 0.35	180°	up to 1.15 T

Inner and outer magnet coils producing field-free region for r < 55 cm

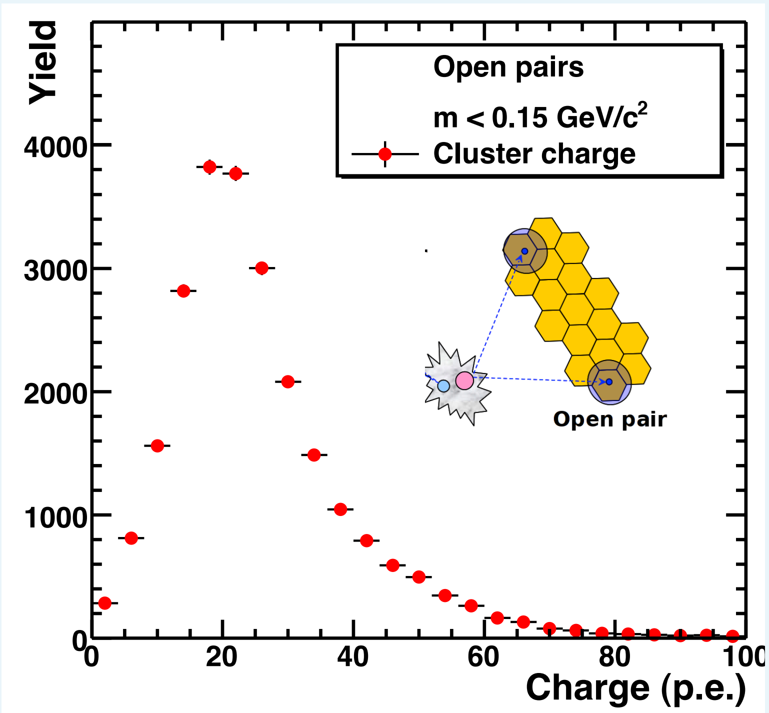
Typically only 1 electron from a pair falls within the PHENIX acceptance.

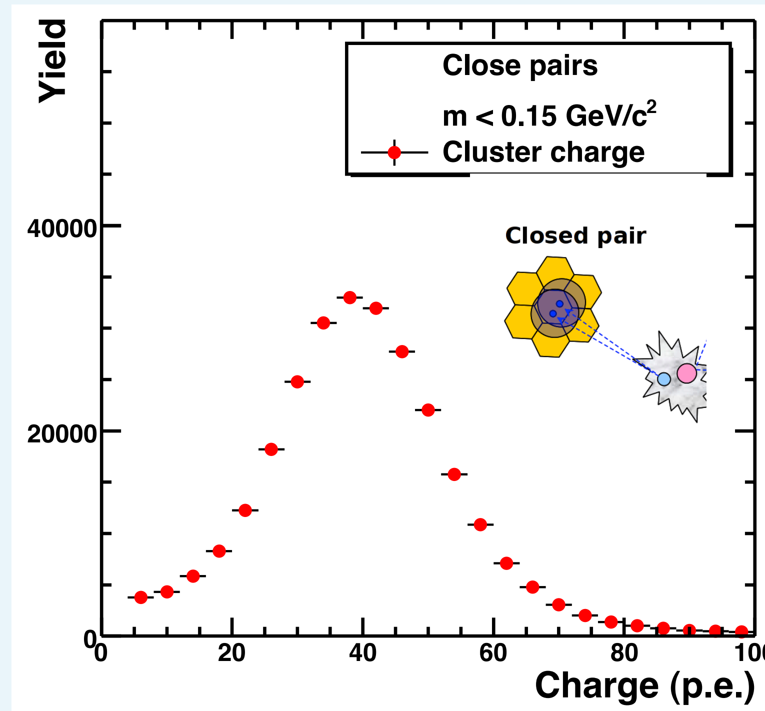
Both members of the pair are needed to reconstruct a Dalitz decay or a γ conversion.

Limited geometrical acceptance of present PHENIX configuration.

Experimental challenge: huge combinatorial background arising from e^+e^- pairs from copiously produced from π^0 Dalitz decay and γ conversions.

HBD Performance





Single electron charge peaks at 20 pe
e+e- large opening angle (>100 mrad)
→ Vector mesons or other signal

Double electron charge peaks at ~40 pe
e+e- small opening angle (<30 mrad)
→ Dalitz or conversion candidate

Good single to double separation

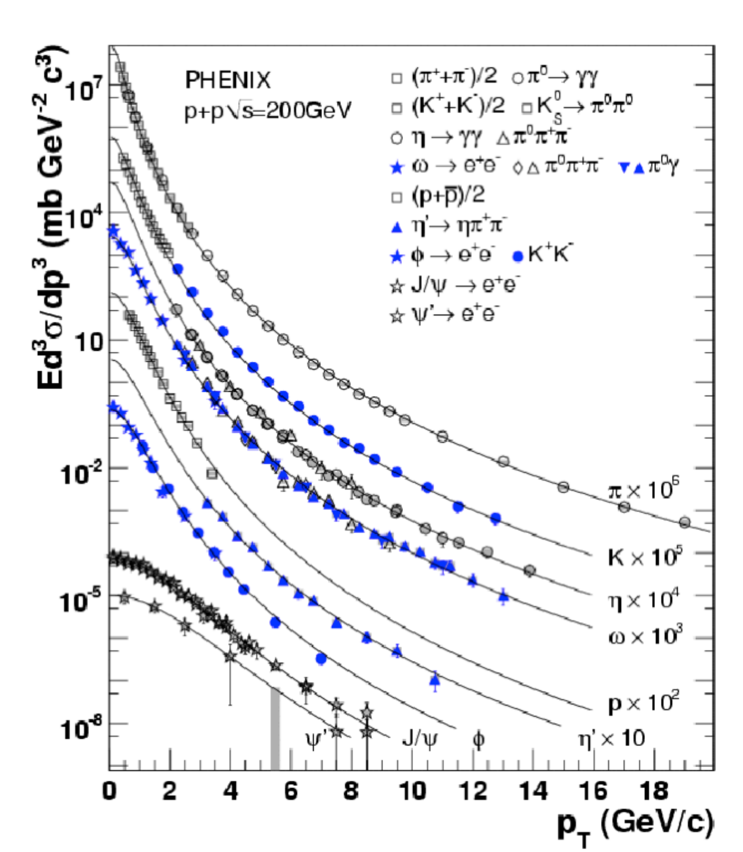
Cocktail

Hadronic cocktail is estimated using measured data from π^0 and charged pions fit to a modified Hagedorn function. m_T scaling is used for shape of other hadrons.

$$E\frac{d^3\sigma}{dp^3} = A\left(\mathrm{e}^{-\left(ap_T + bp_T^2\right)} + p_T/p_0\right)^{-n}$$

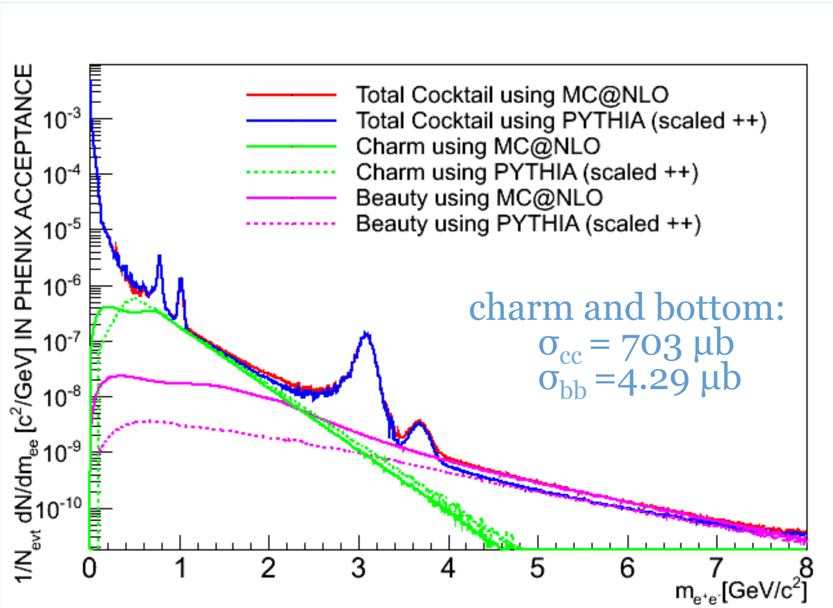
$$p_T \rightarrow \sqrt{p_T^2 - m_{\pi^0}^2 + m_h^2}$$

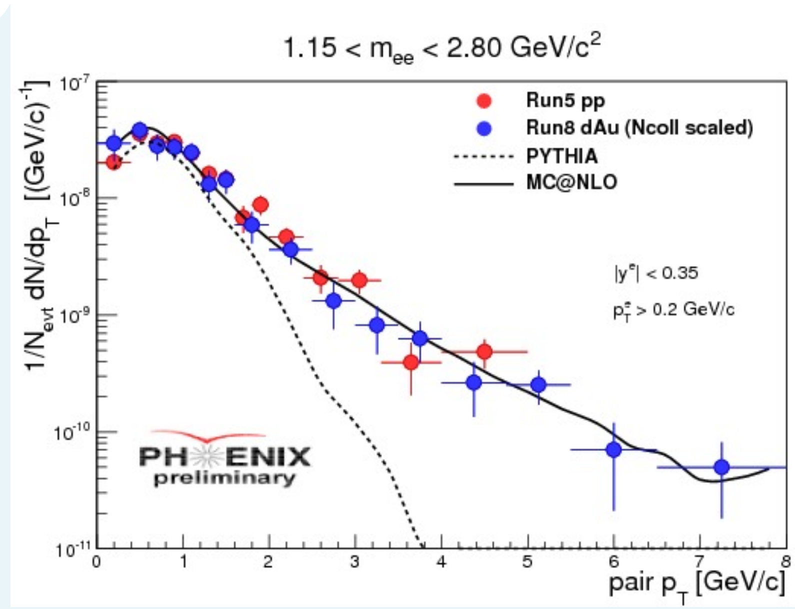
Open heavy flavor (c,b) contributions determined using MC@NLO



PRC 81, 034911 (2010)

MC@NLO

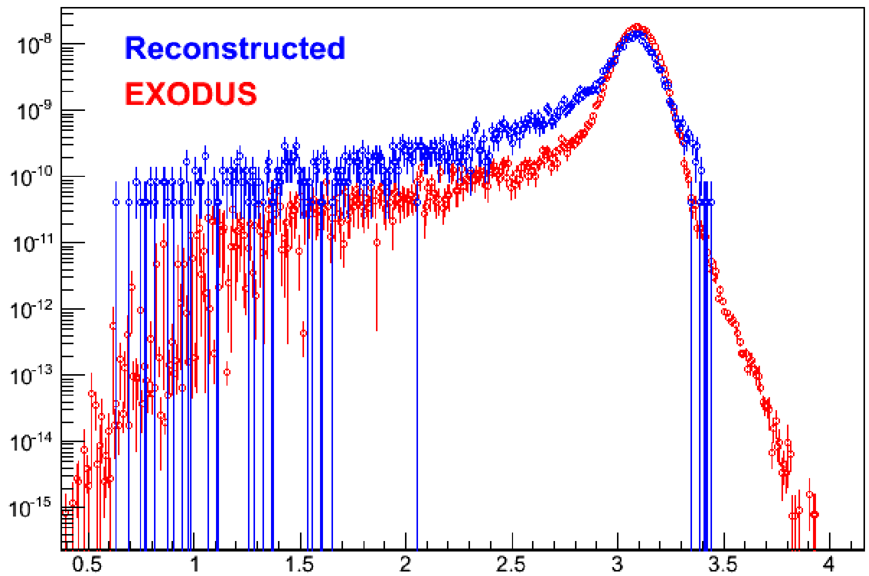


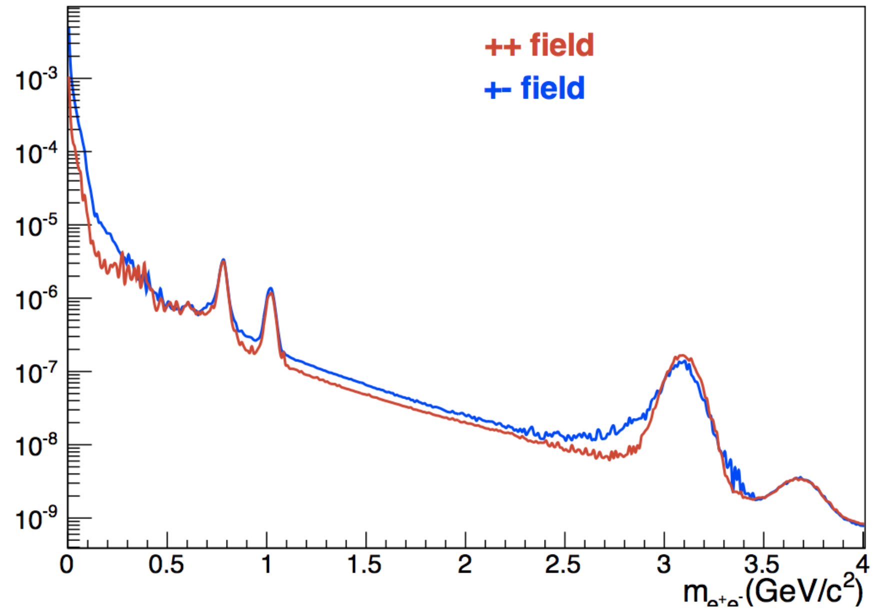


Negligible difference in total cocktail when using PYTHIA vs MC@NLO for open heavy flavor.

MC@NLO reproduces the measured pT distributions of e+e- pairs as opposed to PYTHIA.

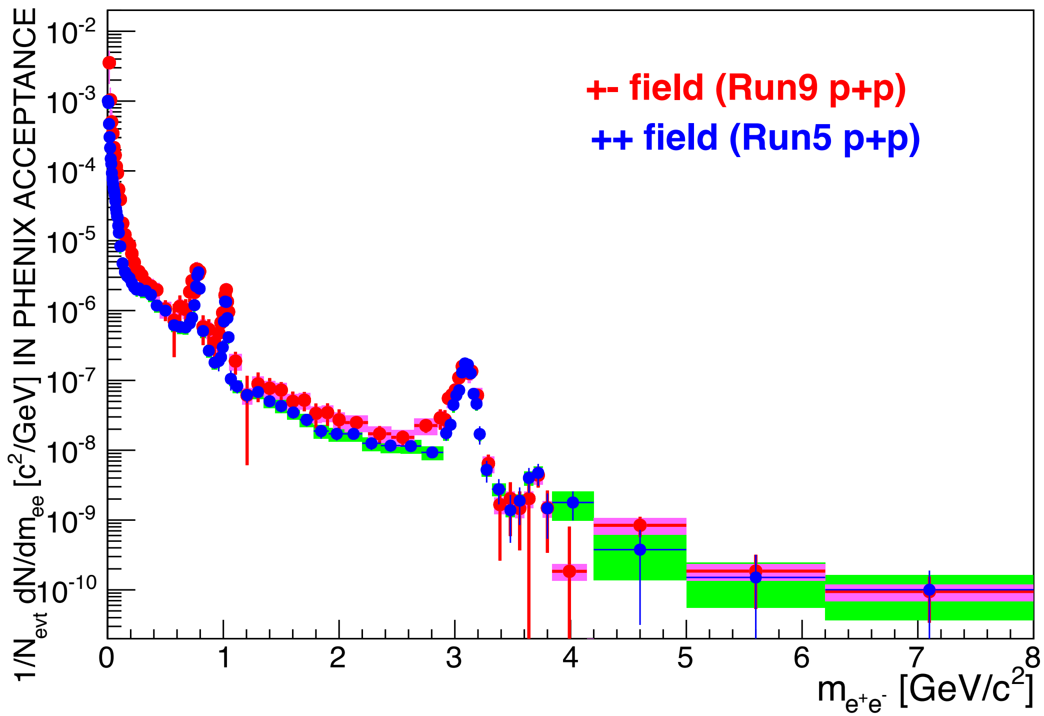
Cocktail Comparison





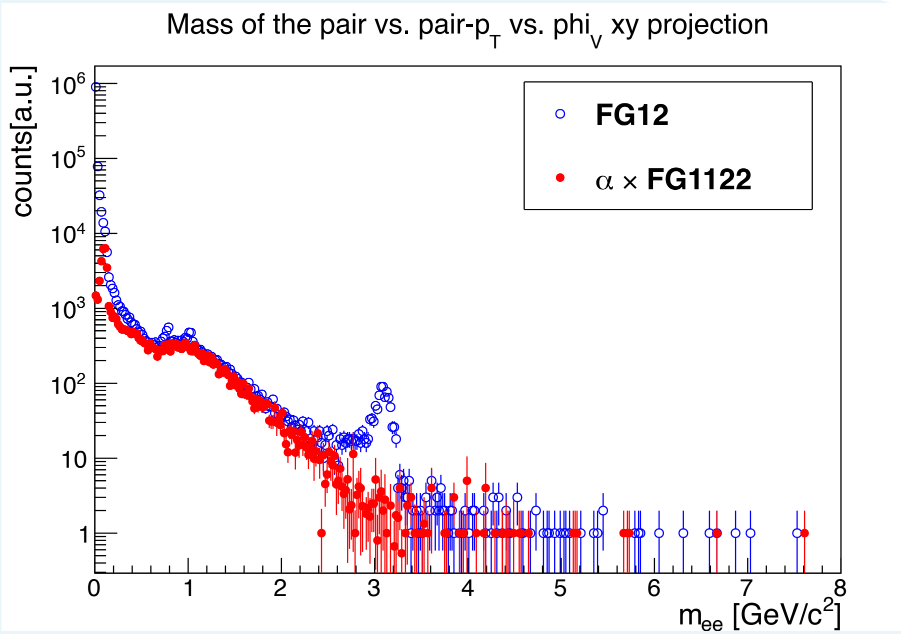
The J/Psi mass is modified to account for detector resolution and radiative corrections. The final cocktail is modified to use the +- field configuration for PHENIX in Run 9.

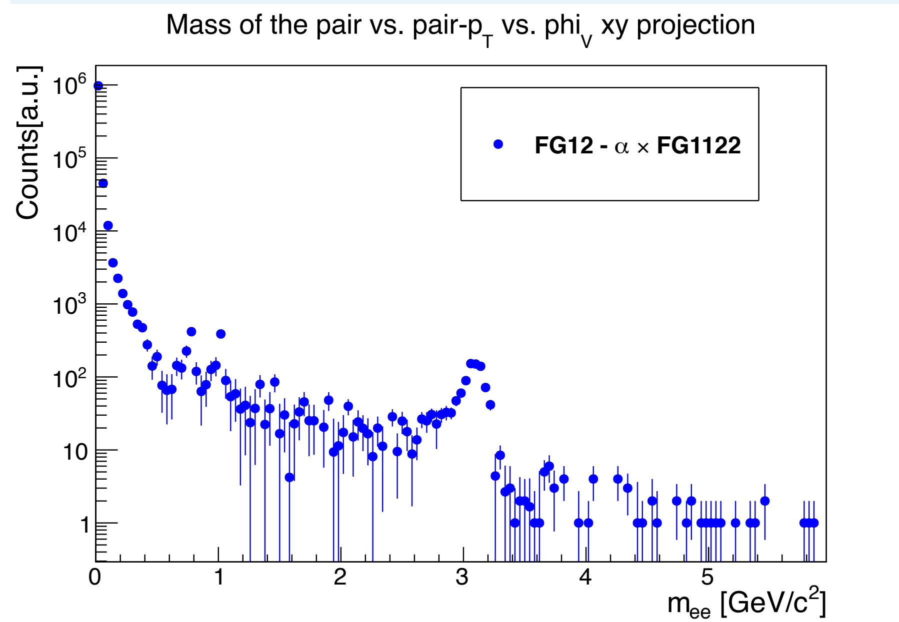
Cocktail Comparison



The dielectron mass spectrum obtained from this analysis compared to the previously published PHENIX Run5 p+p analysis.

Background Subtraction





- Like sign subtraction technique is used to remove combinatorial background and correlated background.

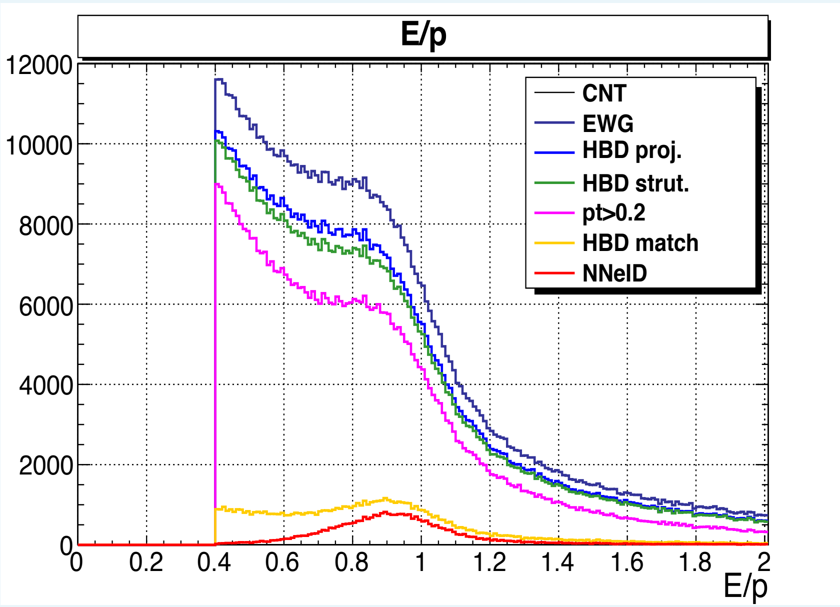
Au+Au analysis Details

Two independent analysis streams: provide crucial consistency check
In both analyses, the combinatorial background is subtracted using mixed events.

Stream A	Stream B
HBD: underlying event subtraction using average charge per pad	HBD: underlying event subtraction using average charge in track projection neighborhood
Neural network for eid and for single/double electron separation	Standard 1D eid cuts and single/ double electron separation
Correlated background (cross pairs and jets) subtracted using acceptance corrected like-sign spectra	Correlated background subtracted using MC for the cross pairs and jet pairs.

Results for stream A will be compared to cocktail: 60-92%, 40-60%, 20-40%
Results for stream B are used as a cross check.
Strong run QA and strong fiducial cuts in both analysis streams

Steps in Analysis

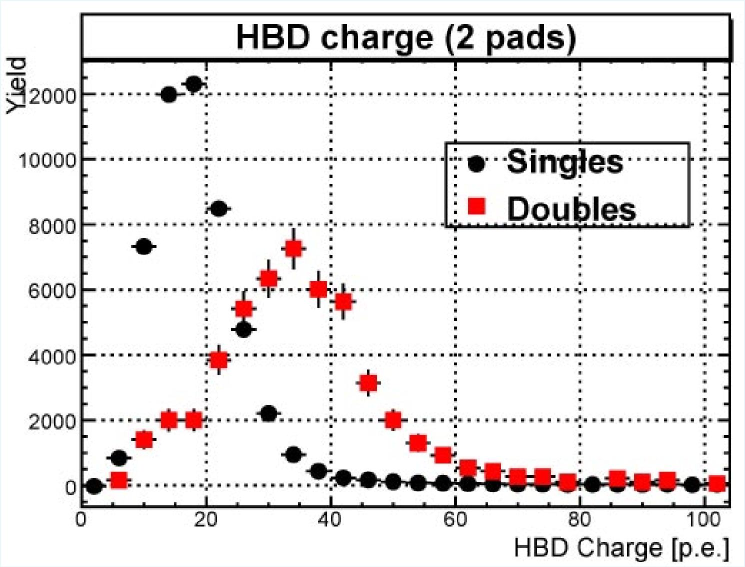


The E/p distribution for each step of the analysis.

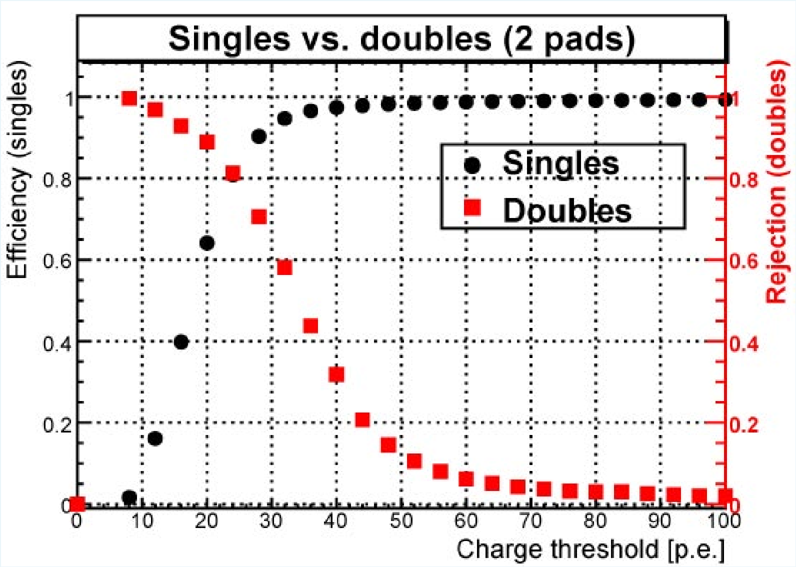
Step in eID
Track reconstruction
Electron selection cut
HBD projection cut
HBD strut cut
pT > 0.2 GeV/c
HBD matching
Neural network eID

NN input variables: E/p, prob, n0, chi2/npe0, disp, hbdid, hbdsize

HBD double Hit Rejection

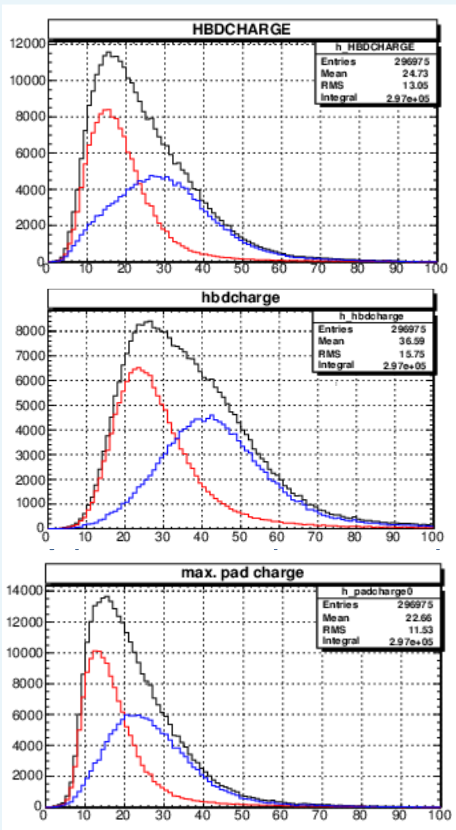


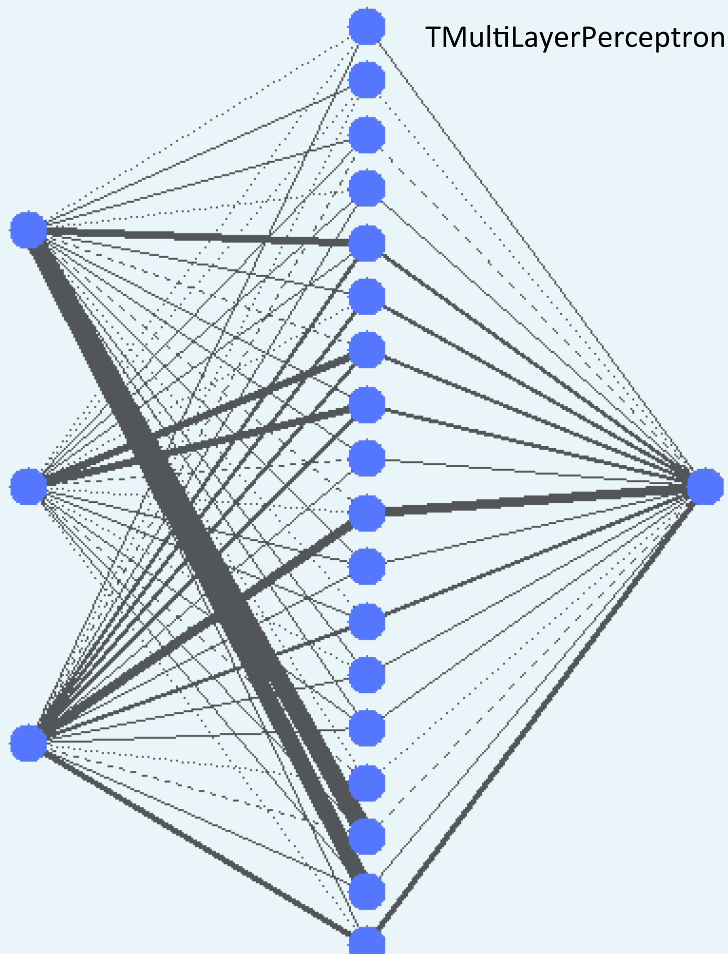
Simulated single and double charge response for clusters containing 2 pads.

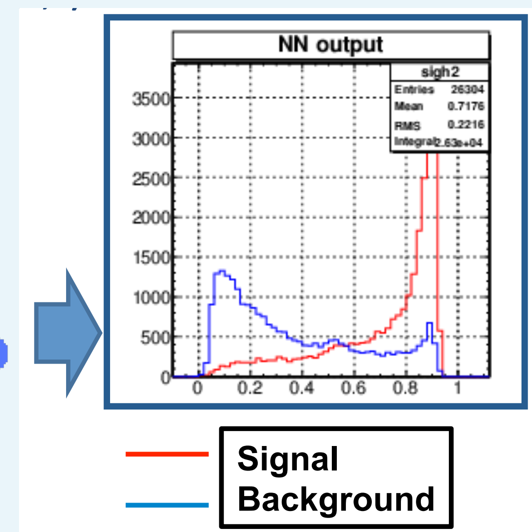


Efficiency and rejection for centrality 70-80%.

Neural Network Details

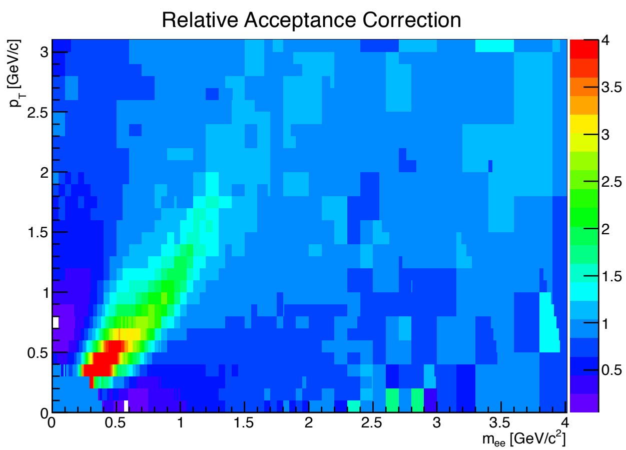


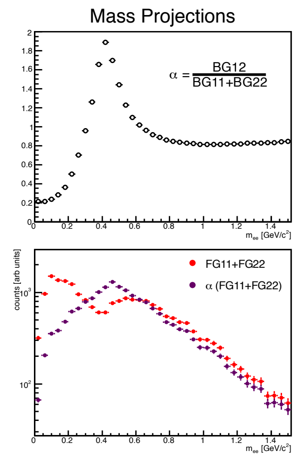




Neural Net output for signal (red) and background (blue) for the givien input variables for centrality 30-40% and HBDSIZE=2.

Background Subtraction





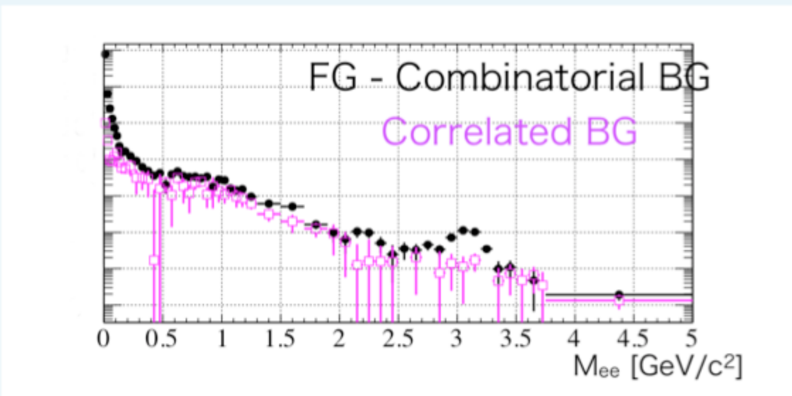
$$S = FG12 - \alpha \cdot FG1122$$

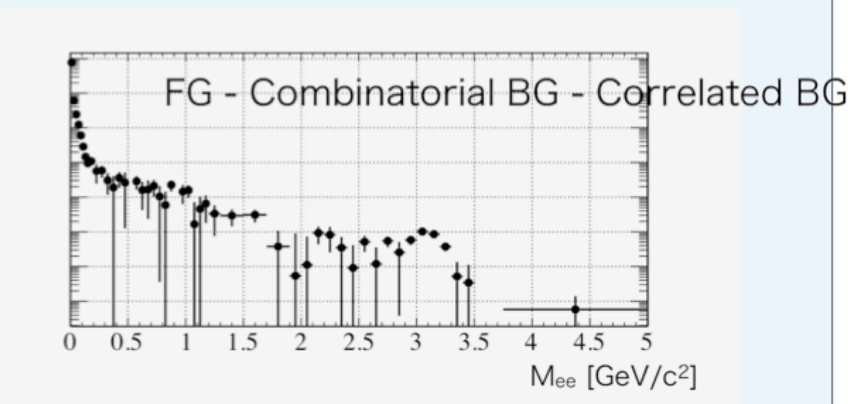
$$S = FG12 - \frac{BG12}{BG1122} \cdot FG1122$$

$$FG1122 = FG11 + FG22.$$

- Assuming that the likesign spectra contain no correlated pairs, the normalization is quite simple.
- However, the assumption of no correlated pairs in the same event likesign distributions is wrong!
- There are indeed correlations that need to be excluded when taking the ratio of (same event)/(mixed event) in the likesign.

Background Subtraction





- Two types of background pairs.
  1. Combinatorial background pairs. (mixed event)
  2. Correlated background pair i.e. $\pi^0 \rightarrow e^+e^-\gamma \rightarrow e^+e^-e^+e^-$ or $\pi \rightarrow \gamma\gamma \rightarrow e^+e^-e^+e^-$, also cross pairs and jet pairs. (acceptance corrected like-sign subtraction)

$$Signal = FG - CombinatorialBG - CorrelatedBG$$

$$CorrelatedBG = \alpha \times \sqrt{(FG11 - N_{11} \times BG11)(FG22 - N_{22} \times BG22)}$$

$$\alpha(m, p_T) = \frac{BG12(m, p_T)}{\sqrt{BG11(m, p_T) \cdot BG22(m, p_T)}}$$

$$S = FG12 - N_{12} \times BG12 - CorrelatedUnlike$$

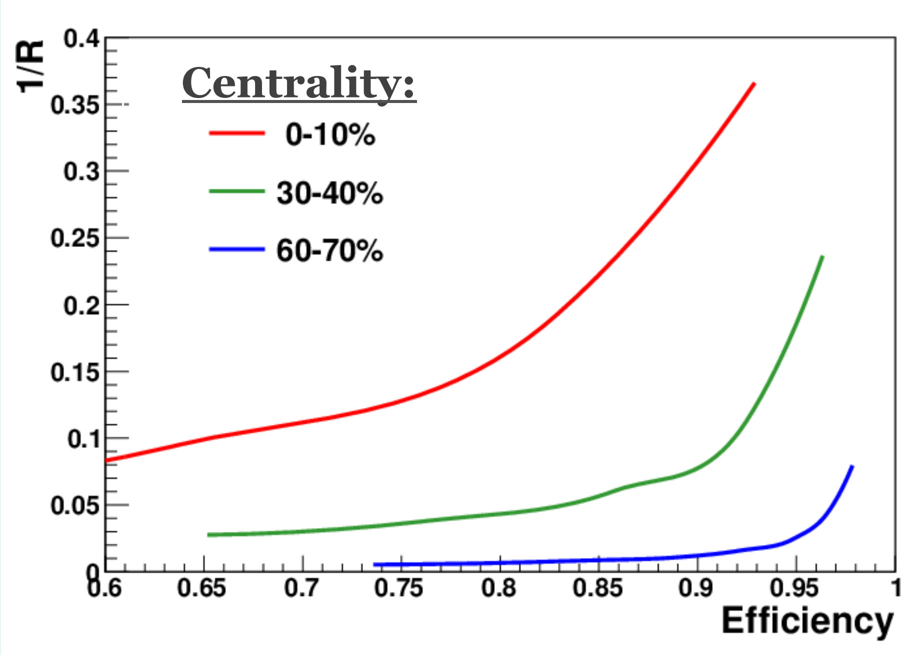
Background Subtraction Issues

- The calculation is performed differentially in mass and pT thereby significantly reducing the statistics in any given bin.
- The S/B is lowest around in this region.
- The like-sign spectrum suffers from a reduction in statistical precision in this region due to the PHENIX two-arm acceptance.
- The relative acceptance correction (α) and it's associated systematic uncertainty are largest in the region mass~0.5GeV/c^2 and pT~0.5GeV/c.

The HBD analysis in Au+Au: matching of tracks to the HBD

<u>Monitoring the efficiency and the rejection</u>:

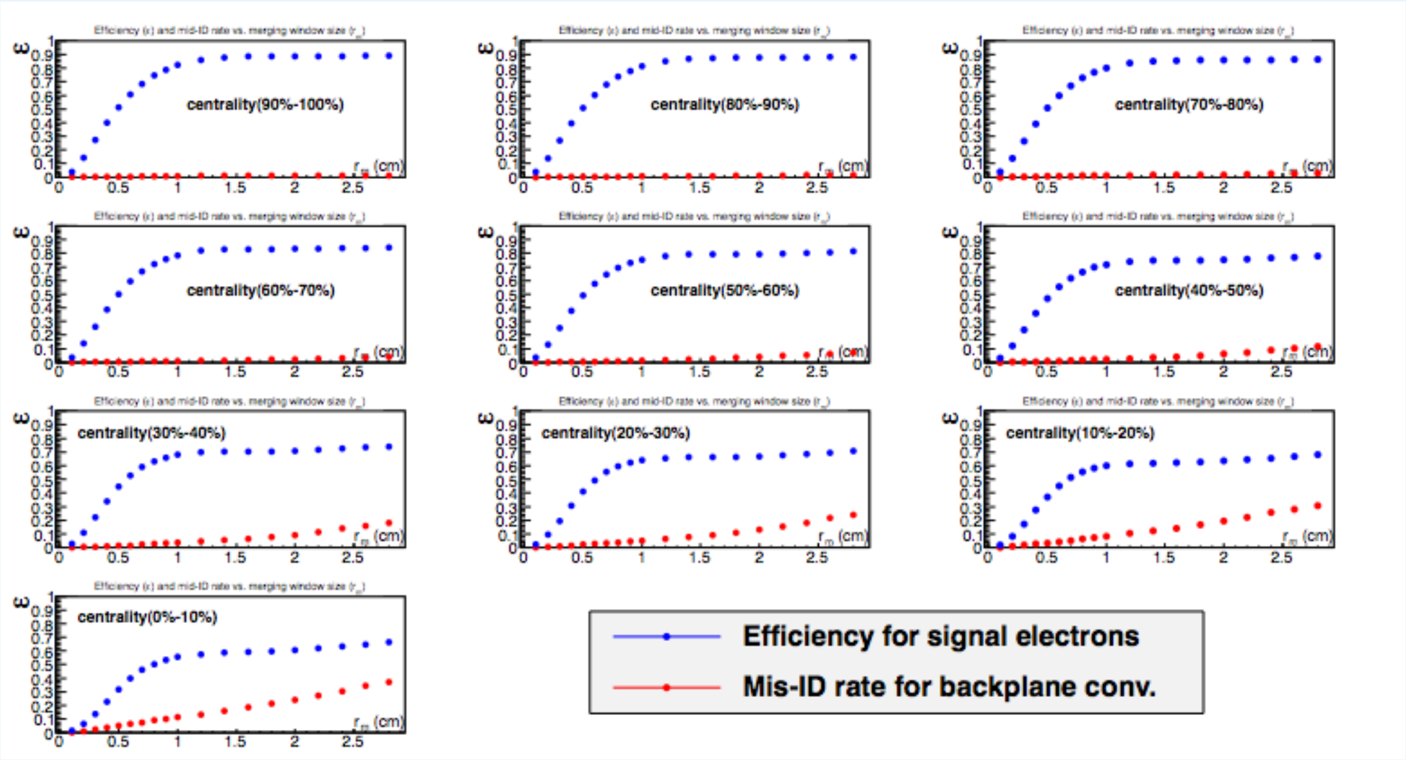
- Efficiency studied using MC electrons from $\phi \to e^+e^-$ embedded in Au+Au data
- Rejection of mis-identified hadrons and random matching determined from the data



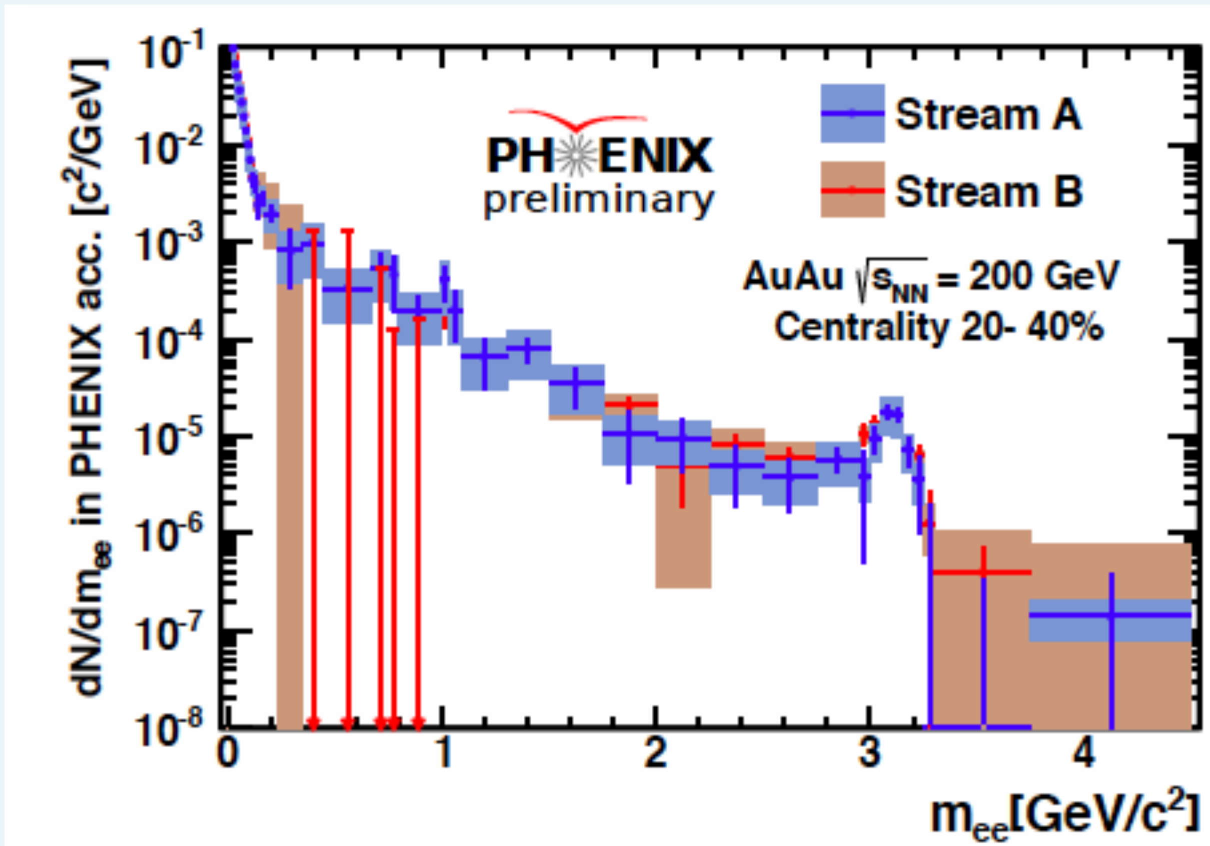
- **Very high rejection achieved while keeping a high efficiency even in the most central events**

Performance in Au+Au collisions

- The SB reconstruction subtracts local background based on triplets around track projections.



Consistency between streams A and B



Direct Photon Elliptic Flow

- PHENIX has measured the elliptic flow of direct photons using a combination of techniques.

$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - v_2^{BG}}{R_\gamma - 1}$$

- R_γ is the fraction of direct photon, $\gamma^{incl}/\gamma^{hadron}$
- v_2^{BG} is the v_2 of photons from hadron decays
- v_2^{inc} is the measured v_2 of all photons

R_γ Via Real and Virtual Photons

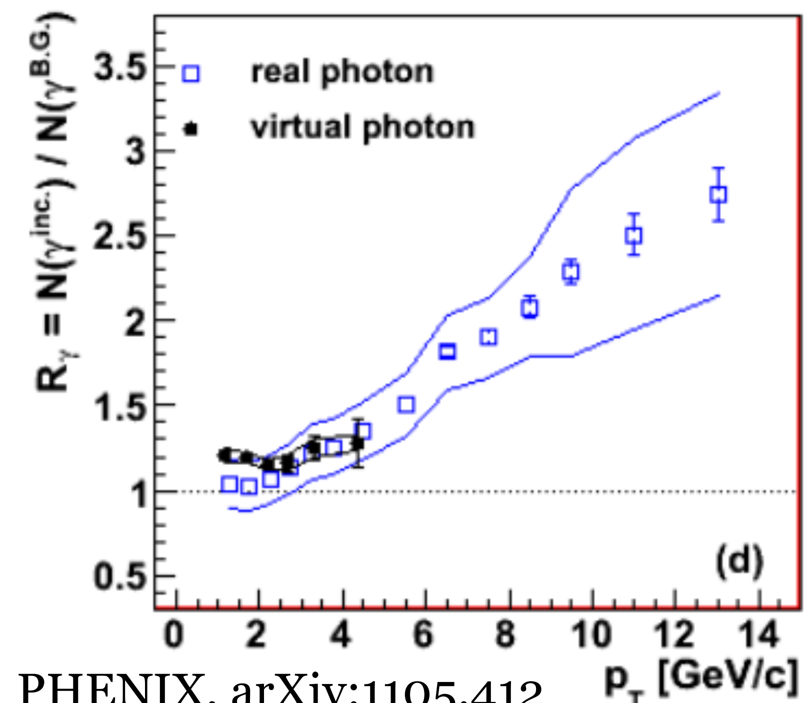
$$R_\gamma = \frac{N_\gamma^{inclusive}}{N_\gamma^{BG}}$$

$$v_2^{dir.} = \frac{\boxed{R_\gamma} v_2^{inc.} - v_2^{BG}}{\boxed{R_\gamma} - 1}$$

Measure through a double ratio

$$R_\gamma = \frac{\gamma^{incl}(p_T)}{\gamma^{hadr}(p_T)} = \frac{\varepsilon_\gamma(p_T) f(p_T) \cdot \left(\frac{N_\gamma^{incl}(p_T)}{N_\gamma^{\pi^0 tag}(p_T)} \right)_{Data}}{\left(\frac{N_\gamma^{hadr}(p_T)}{N_\gamma^{\pi^0}(p_T)} \right)_{Sim}}$$

Tag photons as coming from π^0 decays. Other decays accounted for with a cocktail



PHENIX, arXiv:1105.412

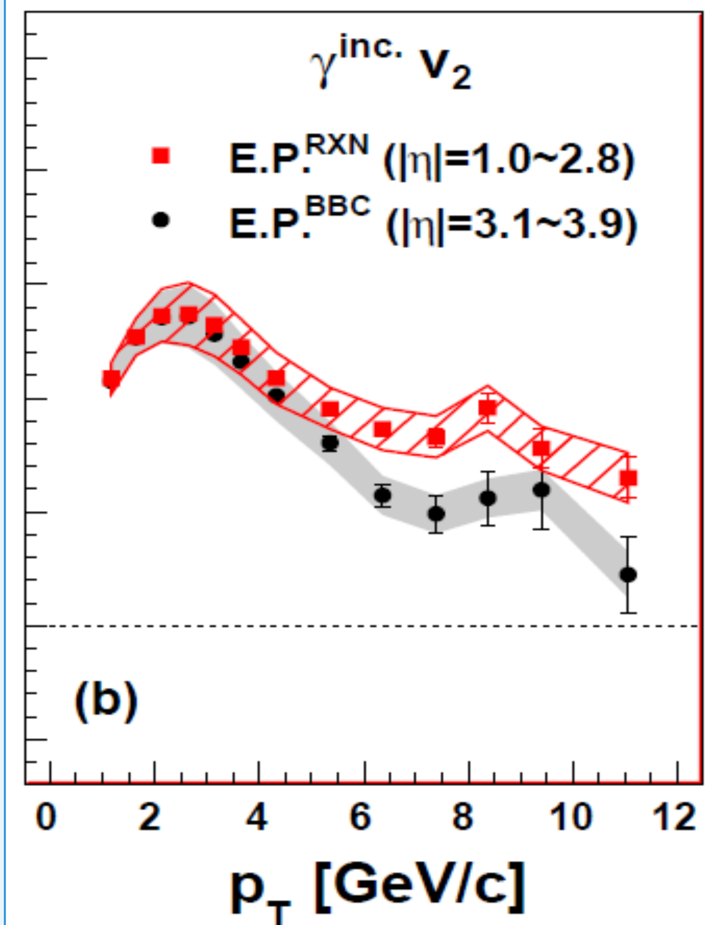
An excess of direct photons above the inclusive sample quantified as a ratio of inclusive to hadronic decay photons.

Inclusive photon v_2

$$v_2^{dir.} = \frac{R_\gamma \boxed{v_2^{inc.}} - v_2^{BG}}{R_\gamma - 1}$$

- Photons measured in the EMCal
- PID consists of
  - Shower shape cut
  - Charged track veto with PC
- Hadron contamination below 6 GeV
  - up to 20% below 2 GeV deposited energy
  - Correct for this with GEANT sim

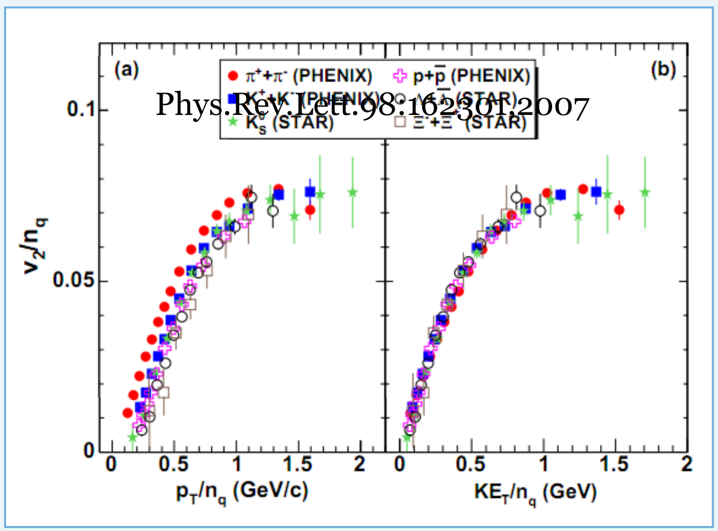
$$v_2^{\gamma,\mathrm{obs}} = \frac{v_2^{\gamma,\mathrm{meas}} - (N^{\mathrm{hadr}}/N^{\mathrm{meas}})v_2^{\mathrm{hadr}}}{1 - N^{\mathrm{hadr}}/N^{\mathrm{meas}}}$$



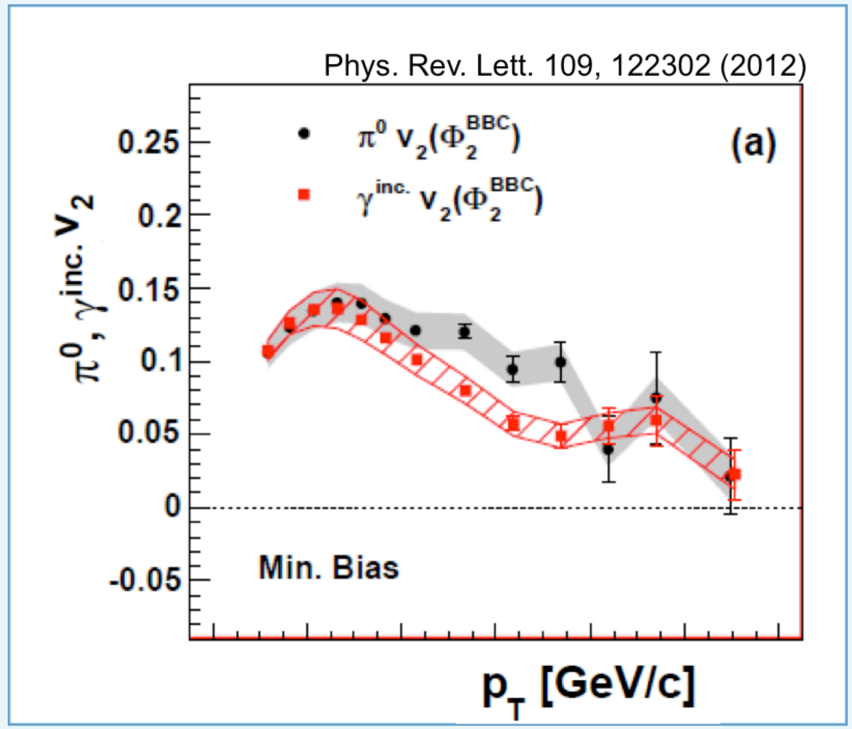
Hadron Decay Photon v_2

- We only measure π^0 v_2
  - about 80% of BG
- Assume v_2 of other hadrons from KE_T scaling
- v_2 modulation put into cocktail
- cocktail gives the total BG v_2 from decay photons

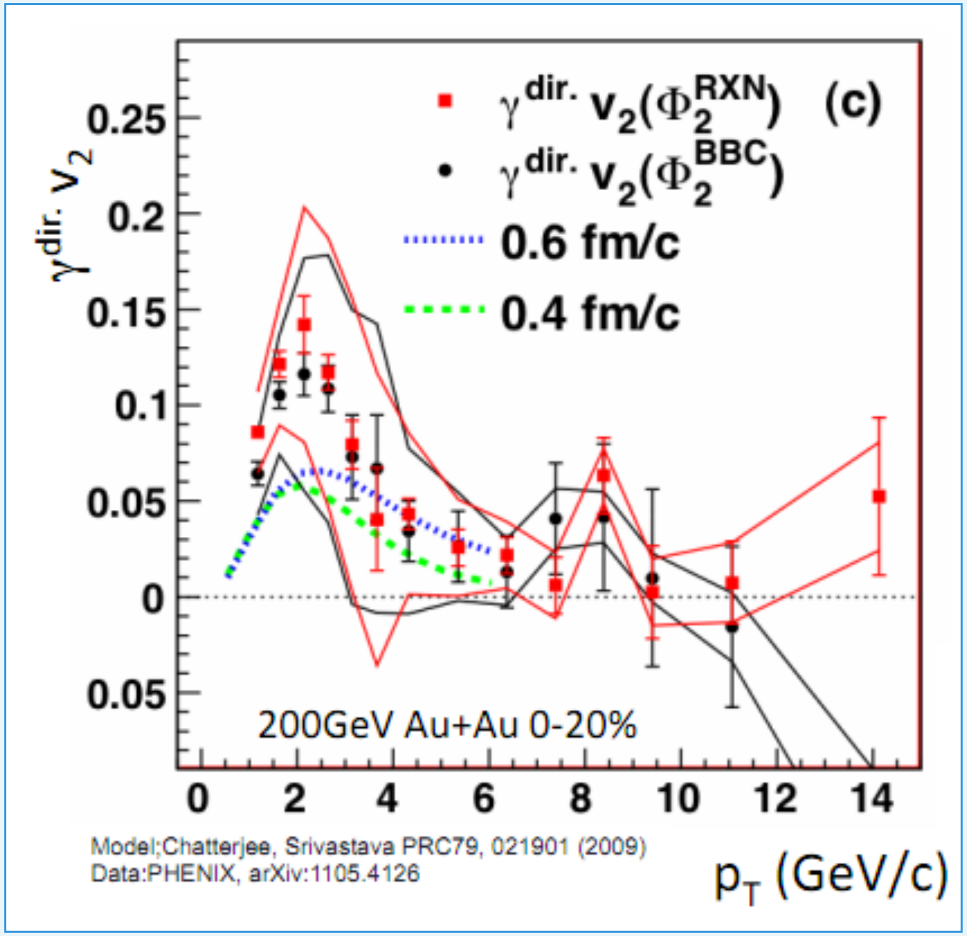
$$v_2^{dir.} = \frac{R_\gamma v_2^{inc.} - \boxed{v_2^{BG}}}{R_\gamma - 1}$$



Phys.Rev.Lett.98:162301,2007



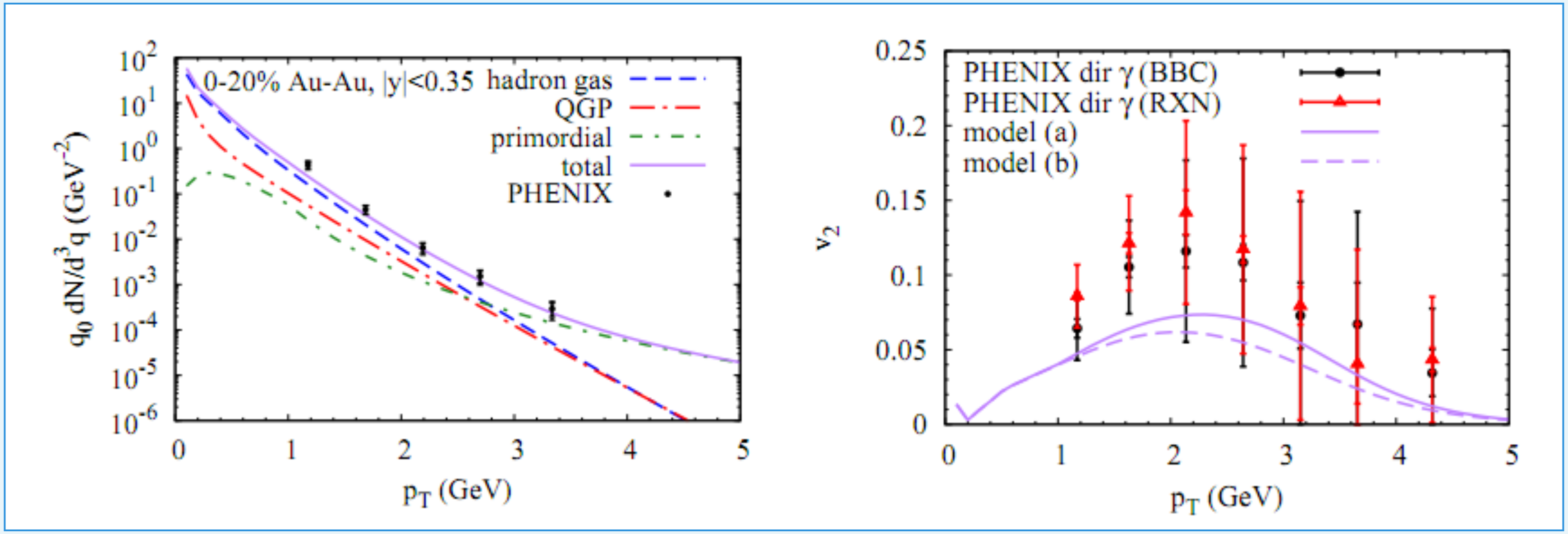
What does it mean? Compare to theory (I)



- Flow takes time to develop
  - QGP photons have small v_2
  - Hadron gas thermal photons have large v_2
- Does not account for data
- Is there something wrong with this picture?

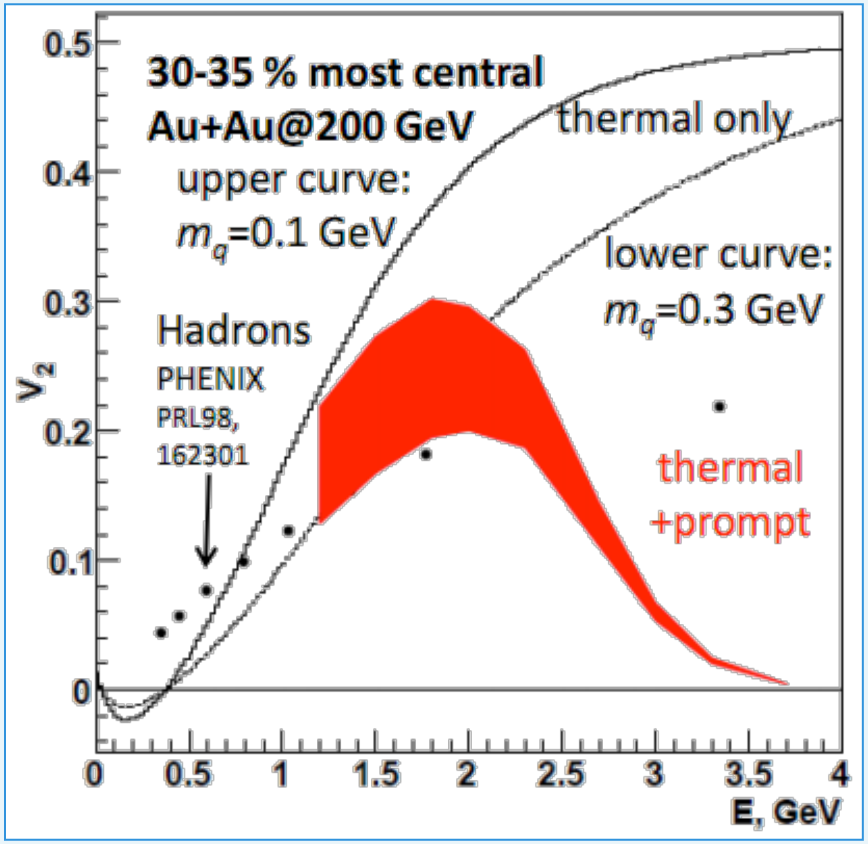
Theory Comparison (II)

H. van Hees, C. Gale, R. Rapp
Phys. Rev. C 84, 054906 (2011)



- Important features/differences from hydrodynamic expansion
  - Hadronic phase includes meson-chemical potentials
  - Hadronic phase lasts longer (smaller T_{fo} and larger T_{ch})
  - Elliptic flow builds up faster
- Thermal radiation dominated by hadronic phase.

Theory Comparison (III)



V. Pantuev, arXiv:1105.4033v1

- Nothing about photon production included in model
  - Assume thermal shape and normalize to data
  - Describes effect of Doppler shift

$$dN/d\omega_0 = exp(-\omega_0/T),$$

$$\omega = \omega_0 \frac{\sqrt{1-\beta^2}}{1-\beta cos\theta}.$$

$$dN/dE = \frac{1-\beta_T cos\theta}{\sqrt{1-\beta^2}} exp(-\frac{E(1-\beta_T cos\theta)}{T\sqrt{1-\beta^2}}).$$

- Cylindrical expanding fireball

Systematic error of direct photon v_2

TABLE I: Representative values of systematic uncertainties contributing to the direct photon v_2 measurement, shown for various p_T ranges for minimum bias collisions

Source	1–3Ǵ eV/c	10–16Ǵ eV/c	Type
inclusive γ v_2			
remaining hadrons	2.2%	N/A	A
v_2 extraction method	0.4%	0.6%	B
π^0 v_2			
particle ID	3.7%	6.0%	A
normalization	0.4%	7.2%	A
shower merging direct γ	N/A	4.0%	B
R_γ	3.1%	22%	A
common reaction plane	6.3%	6.3%	C

PHENIX, arXiv:1105.4126